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THESIS

ORIGIN OF SWELL RECORDED AT MONTEREY, CALIFORNIA

by

Wayne J. Braunstein

September 1970

Thesis
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United States
Naval Postgraduate School

THESIS

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Wayne J. Braunstein

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Origin of Swell Recorded at Monterey, California

by

Wayne J. Braunstein
Lieutenant (junior grade), United States Navy
B.Sc., United States Naval Academy, 1969

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
September 1970

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ABSTRACT

Selected swell wave records from Monterey, California and the associated weather maps were analyzed to determine at what stage in the storm history the peak energy in the swell trains was produced. The apparent origin of the swell, derived by frequency-time analysis of the wave records, was found to lie within the fetch determined from the weather maps, and to occur during the stage in the storm history when the fetch velocity was rapidly decreasing. The group velocity of the peak energy swell was found to equal the fetch velocity at the time of swell origin, a condition suitable for the generation of large wave energy because of a long effective wind duration. By assuming fully arisen seas at the apparent swell source, an average value of the ratio of surface to geostrophic wind speed of 0.77 was obtained. This value was derived from surface winds obtained from the wave data and geostrophic winds obtained from the weather maps. These results confirm the assumption that the peak energy swell was generated in fully arisen seas, and that no shift occurred in the peak swell period in shallow water off Monterey.

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Special thanks are extended to my advisor, Prof. Warren C. Thompson, who suggested and guided this investigation. His experience, efforts, and encouragement, as well as his patience, were invaluable to this author throughout the course of the study.

I. BACKGROUND AND OBJECTIVES

The origin of ocean swell observed to arrive on a coastline has long been associated with storms at sea. However, it has only been in recent years that the characteristics of the swell have been quantitatively analyzed in order to identify their sources. These investigations have been few in number but their results are of great interest.

In a pioneering study on ocean swell by Munk [1947], the invisible forerunners preceding the visible swell were analyzed for their rate of change of period and this information was used to track several oceanic storms in the North Pacific Ocean. A subsequent study by Barber and Ursell [1948] made use of the time rate of increase in frequency to locate the storm sources of several swell trains in the North Atlantic. More recently, in a highly sophisticated study of swell arriving at San Clemente Island, Munk, et al. [1963] analyzed spectrally a great many wave records to determine, with fine resolution, the direction of propagation of the swell sets and to therefore determine their origin with greater accuracy. A later study by Snodgrass, et al. [1966] was equally as sophisticated and expensive; it involved the tracking of swell trains from station to station across the Pacific, from their sources in the Southern Hemisphere to the Alaskan coast. Most recently, Thompson [1969] has shown that the frequency-time relationships for swell arriving on the California coast from North Pacific storms can be derived by simple manual analysis of conventional wave records, and this has yielded good results when used to identify the swell-generating storm systems.

All of these studies have concerned themselves with either the identification of the swell sources or the tracking of storm systems by means of wave records. An important question that remains to be answered is that of the point or stage in the life-cycle of oceanic storms at which swell observed at a distant location are generated. One aspect of this question is the determination of the storm conditions responsible for producing the energy peak in the recorded swell trains. This study represents an attempt to answer this question.

In this investigation, five swell sets recorded at Monterey, California were selected for study, and the storm systems producing the swell were identified by means of frequency-time analyses and by the use of weather maps. The history of the swell-generating area of each storm was then constructed, and was correlated with the history of the swell train recorded at Monterey in order to determine at what stage in the storm development the peak wave energy originated. All analyses were performed manually.

II. SELECTION AND ANALYSIS OF WAVE RECORDS

A. SELECTION OF WAVE RECORDS

All of the wave data used in this study were obtained from the Naval Postgraduate School wave sensor which is a pressure device located 700 feet offshore from the School beach in 25 feet of water (Figure 1). A number of analog strip-chart recordings from this sensor have been manually analyzed by Prof. Warren C. Thompson of the Postgraduate School's Department of Oceanography. From the swell trains that he analyzed, five swell sets were chosen for this study. The selection of these swell sets was determined by the period and height characteristics displayed by the swell, as discussed further below, and by the availability of appropriate weather maps. The swell sets selected for analysis are listed in Table I.

B. PERIOD AND HEIGHT ANALYSIS

1. Period Analysis

The wave data were obtained from the fast-trace section of the analog records, which were of ten-minute duration at three-hour intervals. The wave periods were measured from individual wave groups consisting of from 2 to 20 waves. The period data derived for the five selected swell trains are presented in Figures 2 through 4.

In the case of swell generated in a distant storm, the distance from the storm to the wave gauge is reflected by the arrival times of the various period components of the swell set. Because the longer periods travel faster than the shorter periods, swell arriving at Monterey from distant sources are characterized by a decrease in period

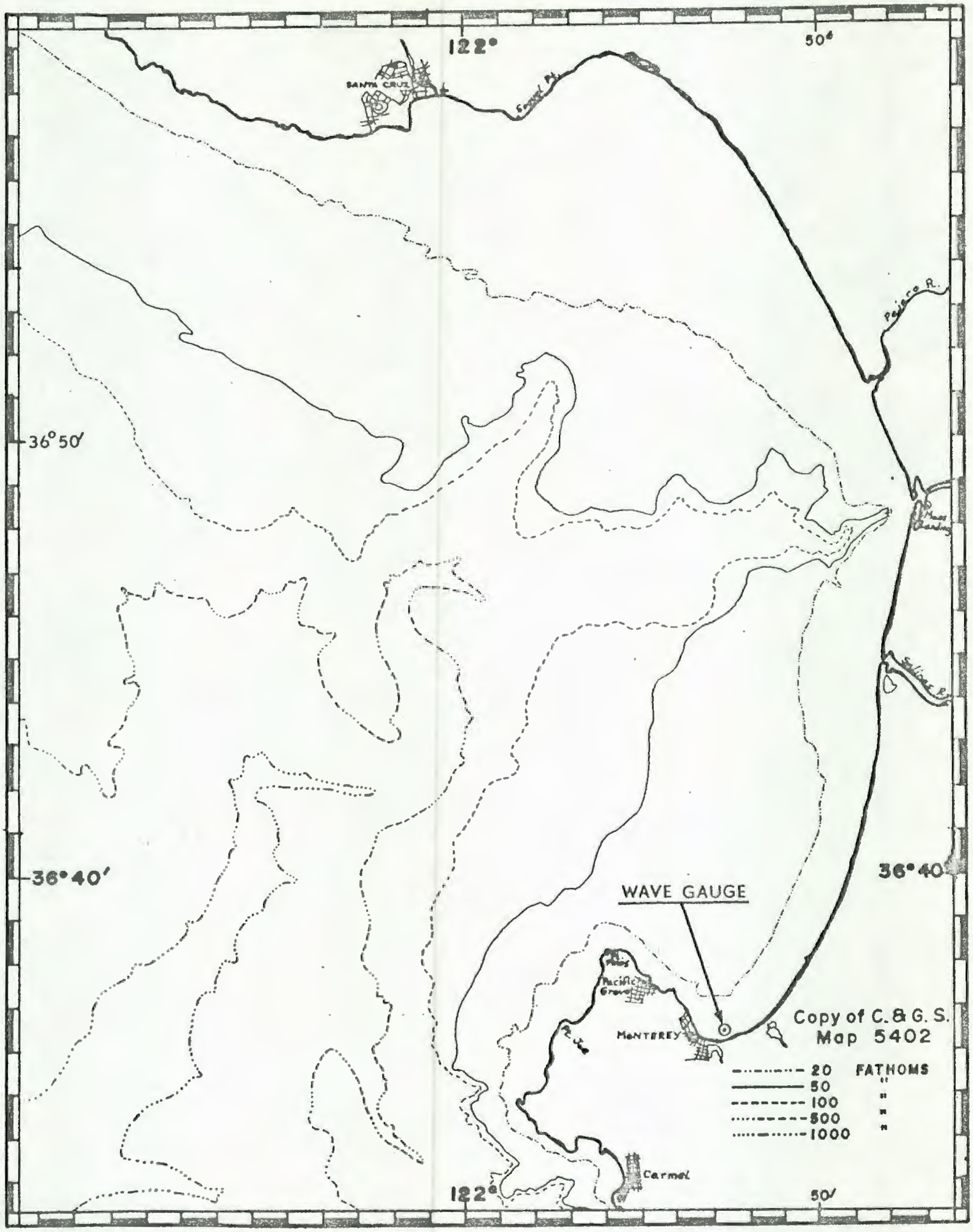


Figure 1: WAVE GAUGE LOCATION IN MONTEREY BAY

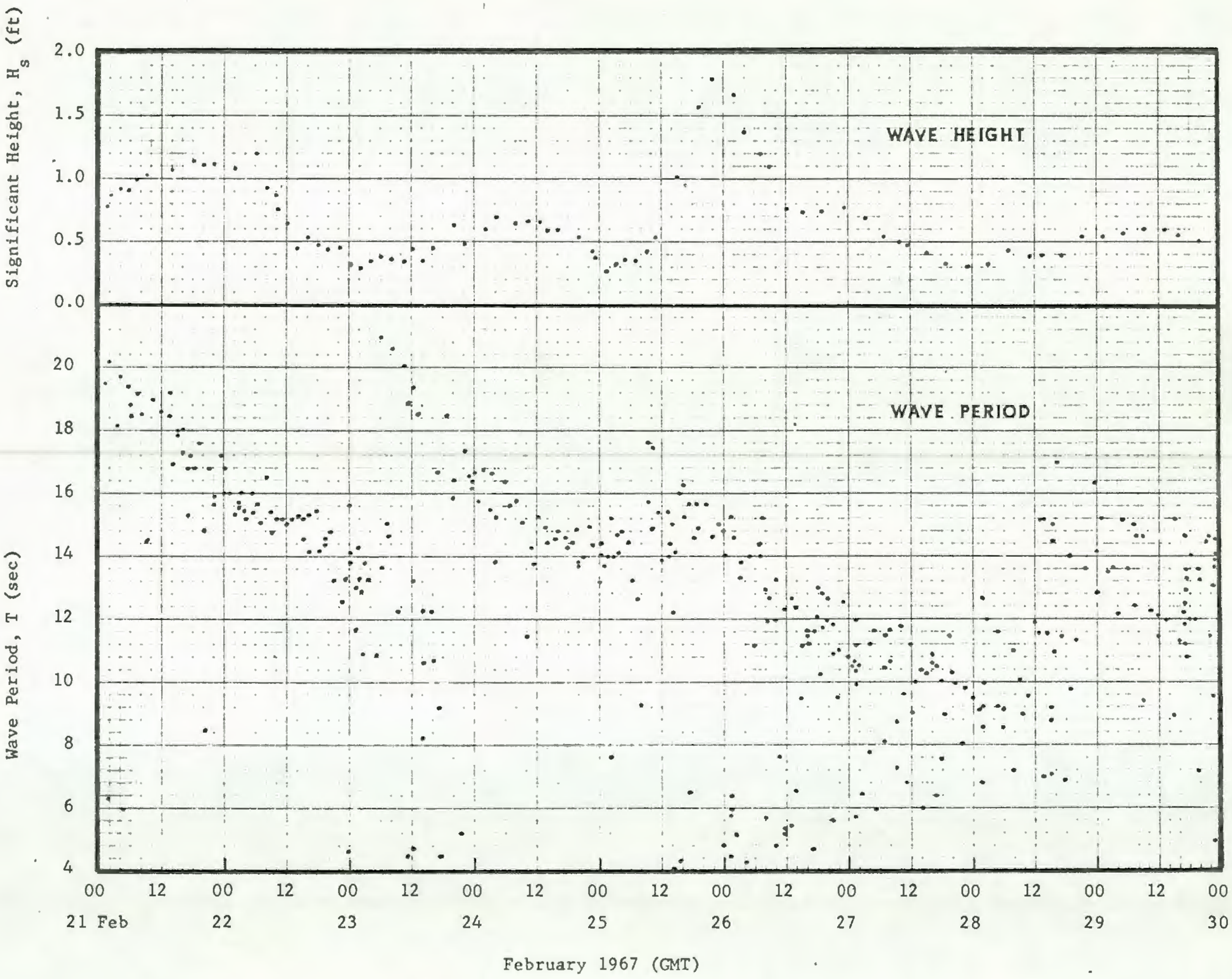


Figure 2: WAVE DATA FOR SWELL SETS 1, 2, AND 3

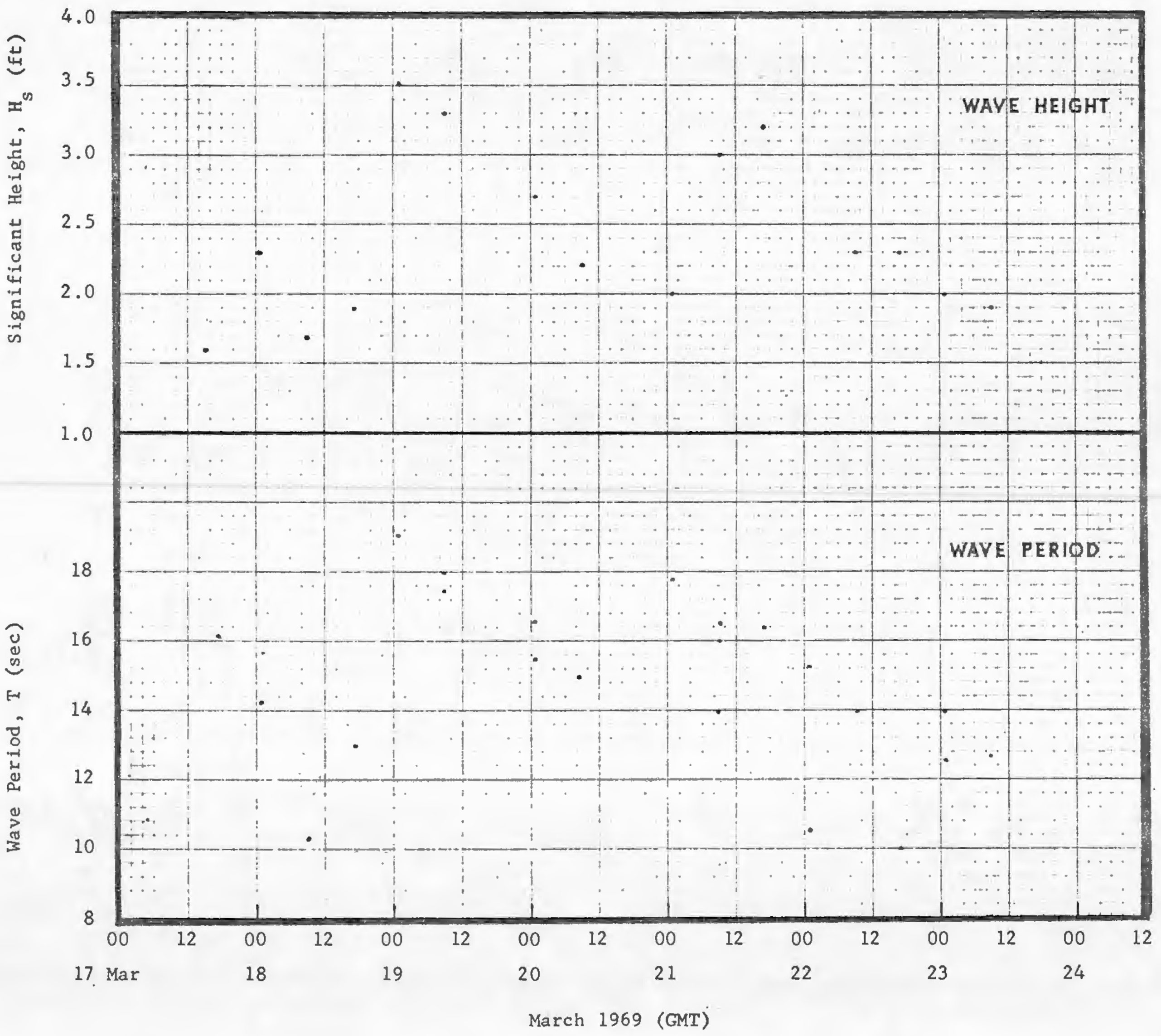


Figure 3: WAVE DATA FOR SWELL SET 4

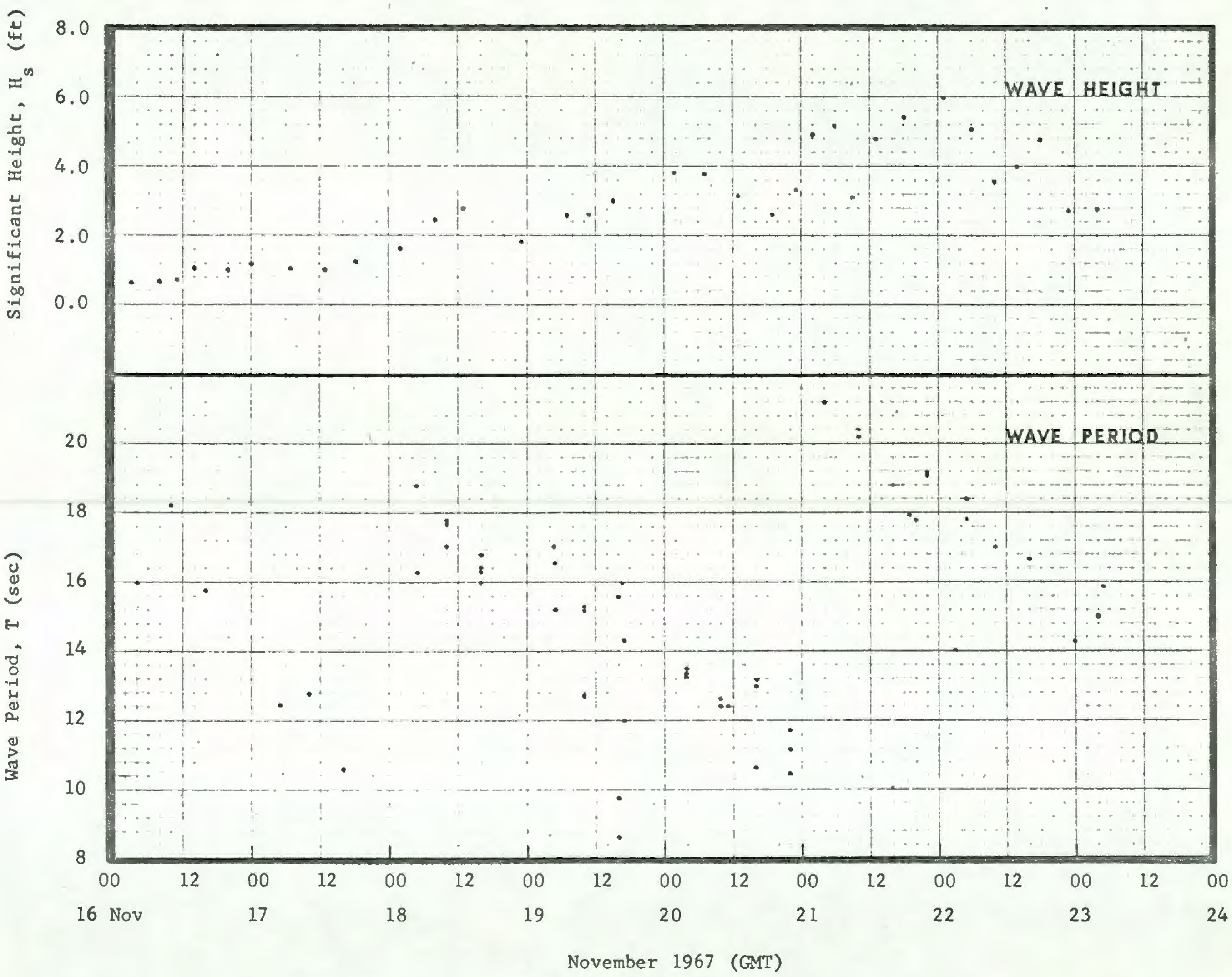


Figure 4: WAVE DATA FOR SWELL SET 5

with time. The amount of this dispersion is directly proportional to the travel distance, and long distances are indicated by a low slope to the period-time distribution and also by a minimum of scatter and a narrow band-width at any moment in the period-time plot. The swell sequences that may be seen in Figures 2 through 4 begin with relatively long periods which indicates an origin in strong wind fields.

In the five cases selected for analysis here, the first periods to arrive ranged from 17 to 22 seconds, and the sequences of decreasing periods were clearly definable to about 10 or 12 seconds, below which low-period scatter obliterated the swell record.

2. Height Analysis

The significant wave-heights, H_s, of the selected swell trains, uncorrected for hydrodynamic damping were derived from the strip-chart records by conventional methods and are shown in Figures 2 through 4. Whereas absolute values of H_s were not required in this study, the time of arrival of the swell peak was important because it determined the period of the peak energy. Factors that may alter the shape of the height-time distribution of the recorded swell from that in deep water immediately offshore, and may thereby affect the time of occurrence of the energy peak and the period of this energy, are discussed below.

a. Hydrodynamic Damping

When considering wave heights recorded on a submerged pressure device, the effect of the overlying water column as a low-pass filter must be taken into account. In the case of the Monterey gauge, which is in a mean depth of 25 feet, the hydrodynamic damping factor, K_H, which may be defined as the ratio of wave height at the bottom to that at the surface, is relatively small for all swell periods dealt with, and varies from 1.13 for 12-second waves to 1.04 for 20-second waves. The rate of change of K_H with T for an arriving swell train is sufficiently small so that hydrodynamic damping does not affect the position of the swell peak.

b. Shoaling

The shoaling effect on the swell height is larger at the sensor site than is the damping effect, and is more pronounced in the longer period portion of the swell than in the shorter periods. However, the rate of change of the shoaling factor, K_S, with wave period in an arriving swell train is sufficiently small so that the shift in the position of the wave-height peak is negligible.

c. Refraction

Differential refraction of the various period components of the arriving swell may also shift the time of the peak wave energy as the swell train travels from deep water to the wave gauge. Refraction factors are not available for the gauge site, but factors have been computed for a location one mile upcoast. The beach and offshore shelf topography (Figure 1) are uniform and similar at both sites so that refraction factors are believed to be similar for the wave directions dealt with. For the deep-water directions from which the selected swell trains arrived off Monterey, the gradient of the refraction factor, K_R, with period is relatively small. Accordingly, differential refraction is believed not to have significantly shifted the position of the wave-height peak.

In view of the small rates of change of K_H, K_S, and K_R, the time of occurrence and period of the peak energy in deep water was concluded to be essentially the same as that indicated by the uncorrected H_S measurements. On the basis of this conclusion, swell sets were selected having reasonably well-defined peaks so that accurate arrival times could be determined for the peak energy. The period data for each swell set were also examined in order to insure that the wave trains selected were indeed swell waves from distant storms and not from local sources. For the swell sets selected to be analyzed, the times of arrival and the periods, T_{pk}, of the peak energy are listed in Table I.

C. FREQUENCY-TIME RELATIONSHIPS

As was stated in the introduction, recent work has shown that the frequency-time (f-t) relationship for swell arriving from a distant storm is linear. For the five swell sets selected for study, the period-time data (Figures 2 through 4) were converted to f-t graphs (Figures 5 through 7), and straight lines were fitted to the scatter of frequency data for each swell set. Using the technique given by Snodgrass, et al. [1966], this linear fit was then used to determine the apparent source of the swell train. The apparent origin time of the swell train was read from the time axis ($f = 0$) at the point of interception by the straight line, and the apparent travel distance was determined from the slope of the line. The implications of designating a point as the source of a swell train have yet to be fully explored and this author has not attempted to do so. However, the apparent origin time and distance are fundamental considerations in this analysis.

The origin times and distances for the five swell sets selected were calculated originally by Professor Thompson and have since been recomputed by this author. This information is summarized in Table I, and its application to the selection of meteorological charts is discussed in the following section.

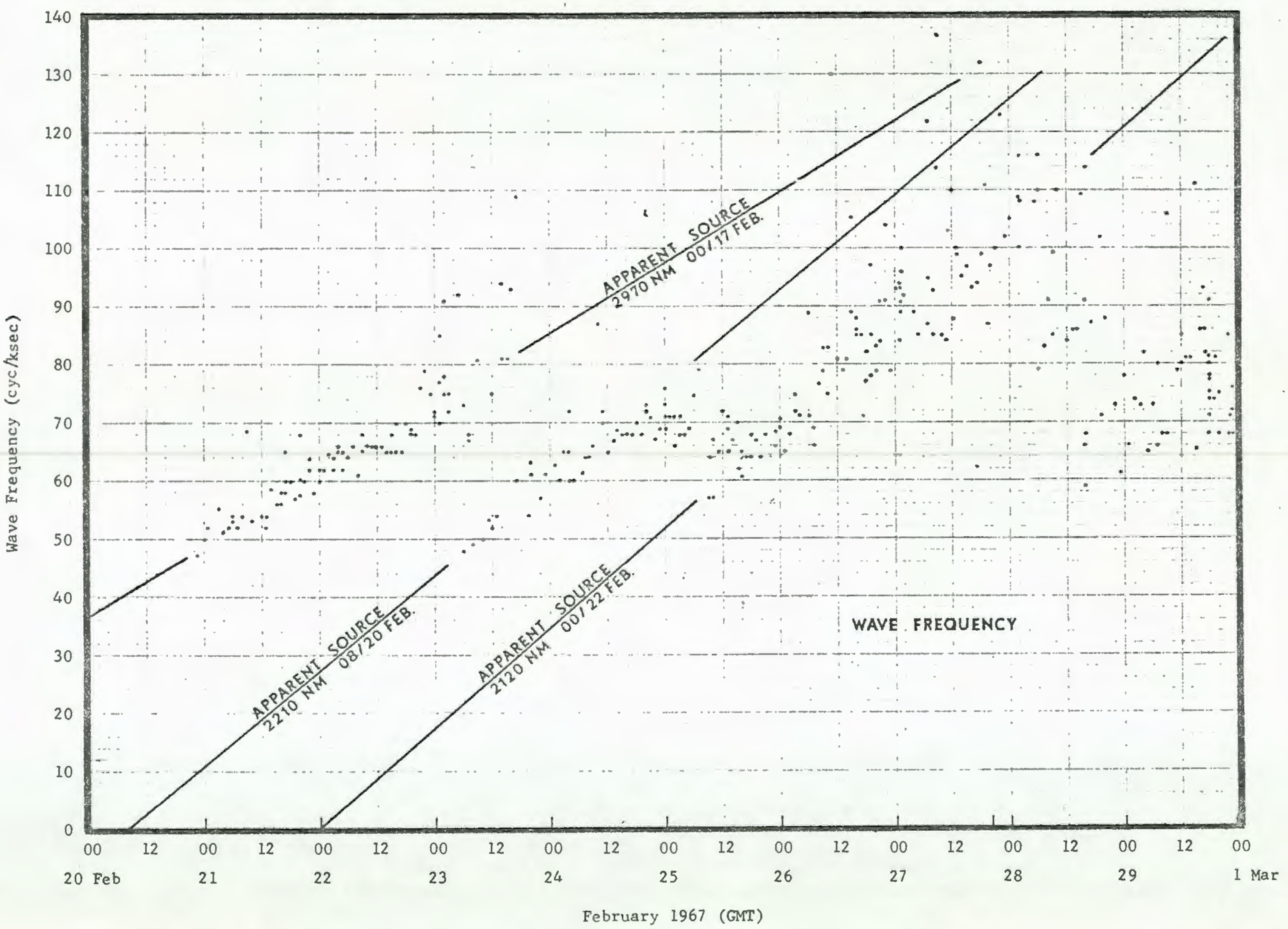


Figure 5: FREQUENCY-TIME ANALYSIS FOR SWELL SETS 1, 2, AND 3

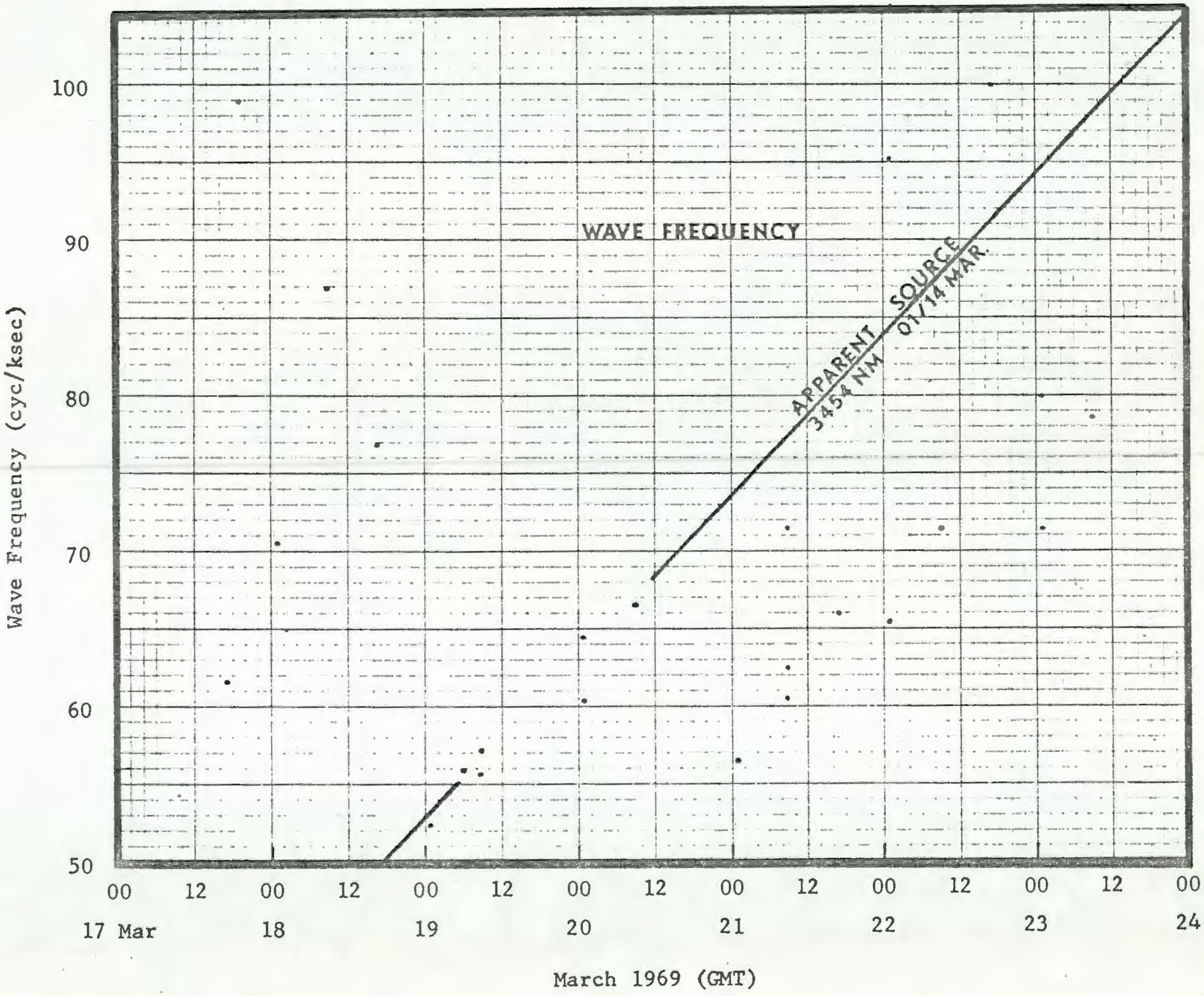


Figure 6: FREQUENCY-TIME ANALYSIS FOR SWELL SET 4

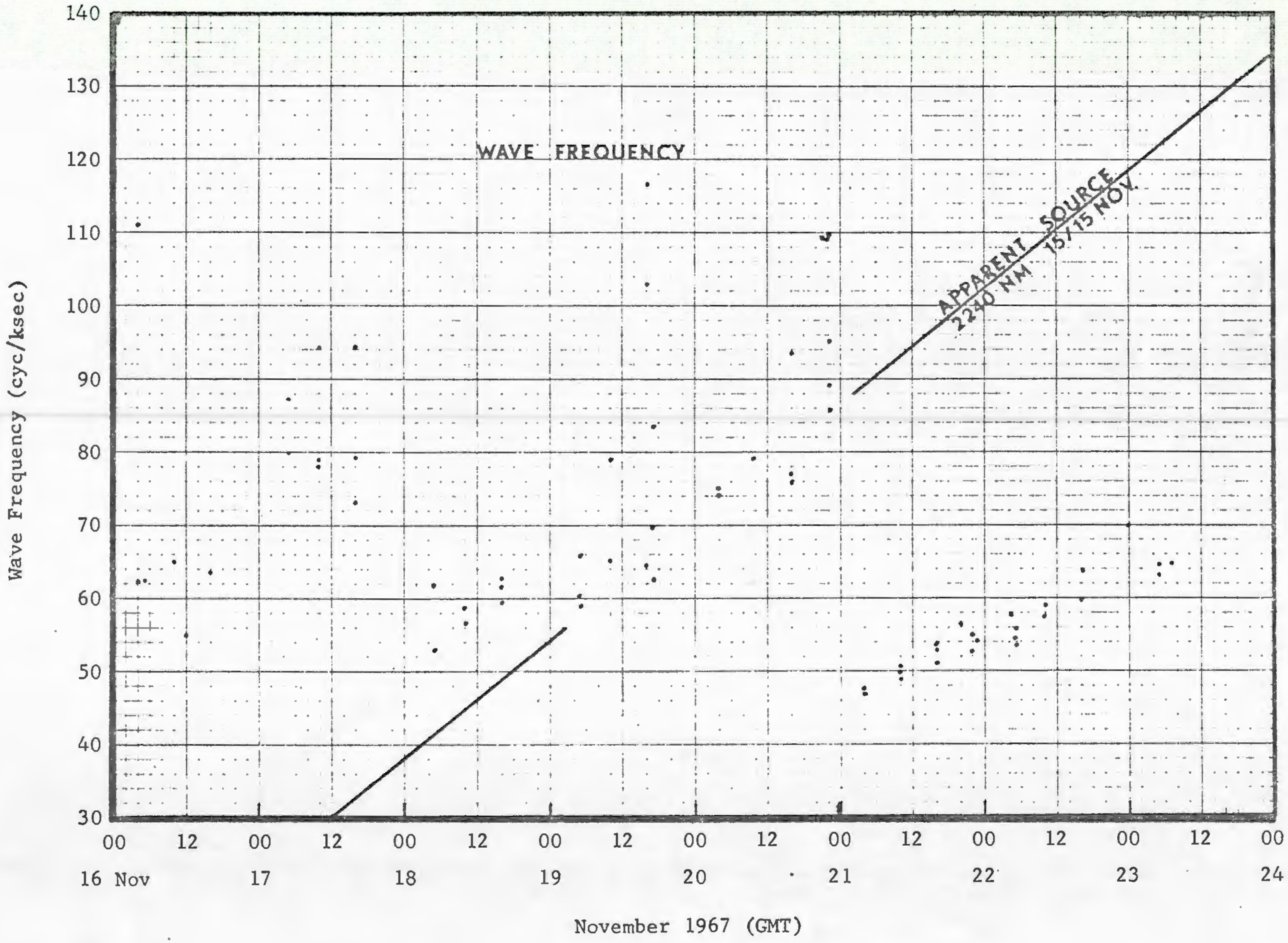


Figure 7: FREQUENCY-TIME ANALYSIS FOR SWELL SET 5

Table I: SWELL DATA

Designation of Swell Set	Arrival Dates (GMT)	Arrival Time of Peak Energy	Period, T_{pk}, of Peak Energy (sec)	Apparent Origin Time (GMT)	Apparent Origin Distance (NM)
1	21-23 Feb 67	2100/21 Feb	17.0	0000/17 Feb	2970
2	22-24 Feb 67	0700/24 Feb	15.6	0800/20 Feb	2210
3	25-28 Feb 67	2300/25 Feb	14.5	0000/22 Feb	2120
4	18-20 Mar 69	0100/19 Mar	19.0	0100/14 Mar	3454
5	18-21 Nov 67	0400/20 Nov	13.7	1500/15 Nov	2240

III. SELECTION AND ANALYSIS OF SEA-LEVEL PRESSURE CHARTS

A. SELECTION OF SEA-LEVEL PRESSURE CHARTS

The sea-level pressure analyses selected for this study are objective analyses produced by the Fleet Numerical Weather Central, Monterey. They were chosen because they covered completely the area of the North Pacific under investigation and were available for six-hour intervals.

The individual charts were chosen on the basis of the frequency-time analyses of the selected swell trains recorded at Monterey. The weather map series was entered for the six-hourly map occurring closest in time to the computed origin time, and the map was scanned for storm systems located at the computed origin distance from Monterey. When the appropriate storm was found, a series of six-hourly charts was selected so as to cover the important part of the history of the storm. The storms selected in this manner were designated by number to agree with the respective swell train and are listed in Table II. In the case of Swell Set 3, the f-t analysis located two possible storm sources, and the histories of both these storms were analyzed.

B. DETERMINATION OF THE FETCH

1. Basic Considerations

In order to identify the stage in the history of the storm at which the energy peak of a particular set of recorded swell waves was generated, it was first necessary to identify, on each six-hourly weather map, that portion of the wind field that could produce waves which would propagate in the direction of Monterey. Also, since the source area of the peak height of the recorded swell train was desired, the wind field was reduced further to a band of high wind energy.

Table II: STORM DATA

Swell Set	Storm Designation	Surface Pressure Maps Used (GMT)	Location of Storm Center on First Map Used
1	1	00/15 Feb--00/17 Feb 67	33°N - 144°E
2	2	18/16 Feb--12/21 Feb 67	40°N - 134°E
3	3A	00/21 Feb--06/23 Feb 67	34°N - 180°W
	3B	00/21 Feb--06/23 Feb 67	46°N - 148°W
4	4	12/11 Mar--18/15 Mar 69	28°N - 129°E
5	5	00/12 Nov--00/16 Nov 67	39°N - 139°E

These directional and energy limitations were of a nature such that the swell-generating sector of the wind field could be analyzed using a standardized procedure from chart to chart and from storm to storm, with a minimum amount of subjective analysis.

The basic limiting considerations in swell generation and the procedure used to construct the desired wind area, hereafter referred to as the fetch, are developed further below.

2. Construction of Reference Line

On each surface pressure chart, a straight line, SM (Figure 8a), was drawn between the low pressure center of the storm being analyzed and Monterey; this line represents a close approximation to a great circle line-of-bearing. It was observed that, for a distant storm, this line-of-bearing did not differ significantly from a line-of-bearing between Monterey and the center of the fetch.

In delineating the fetch on a given weather map, it was first necessary to limit the wind field so as to consider only those winds which met certain directional criteria [Sverdrup and Munk, 1951]. This was done by assuming that only those winds blowing at an angle of 45 degrees or less across the line-of-bearing are responsible for the waves recorded at Monterey. The hatched area of the circular wind field illustrated in Figure 8a includes all the geostrophic winds which meet this criterion. However, in considering direction, the surface wind direction was desired and was assumed to deviate from the geostrophic wind by 15 degrees in the direction of the storm center. The hatched area of Figure 8a was therefore rotated 15 degrees clockwise about the storm center in order to satisfy the 45 degree angle criterion for surface winds. Thus the hatched area in Figure 8b contains the geostrophic winds which produce surface winds having the desired directional limitations.

An important assumption in this study is that of all the waves generated in this area, those propagating in a direction parallel to line SM would arrive at Monterey with the greatest amount of energy. These waves would be generated by surface winds blowing parallel to SM, which may be represented by geostrophic winds directed 15 degrees to the right of SM. The line along which these geostrophic winds were located, which bears 105 degrees from SM, is shown as line SR in Figure 8b and is hereafter referred to as the reference line.

3. Geostrophic Wind Calculations

After constructing the reference line on the surface pressure chart, the geostrophic wind speeds were calculated along its length. Three-isobar spacing (12 mb) was used to compute the geostrophic wind speed at intervals along the reference line beginning at the center of the storm and proceeding outward. The mid-point of each successive three-isobar interval was used as the location of the computed wind speed for that interval; the distance of this mid-point from the center of the storm was also measured. The winds were calculated using the geostrophic equation:

$$V_g = \frac{K}{2\Omega \rho \sin \Phi} \frac{\Delta p}{\Delta n}$$

where V_g = geostrophic wind speed in knots

Δp = pressure differential in millibars

Δn = distance differential in degrees latitude

Φ = latitude

$\rho = 1.26 \text{ gm/cm}^3$

$\Omega = 7.29 \times 10^{-5} \text{ sec}^{-1}$

$K = 1.725 \times 10^{-3}$, units conversion factor

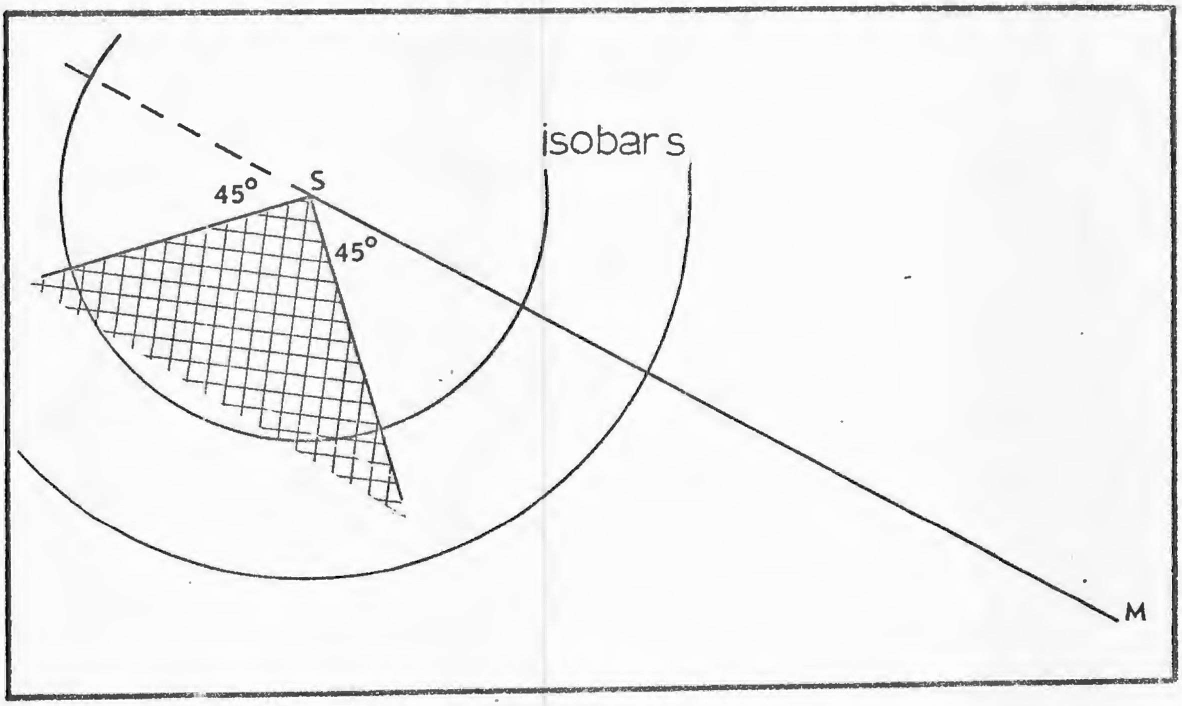


Figure 8a: INITIAL DETERMINATION OF THE WIND FIELD BASED ON GEOSTROPHIC WIND DIRECTION

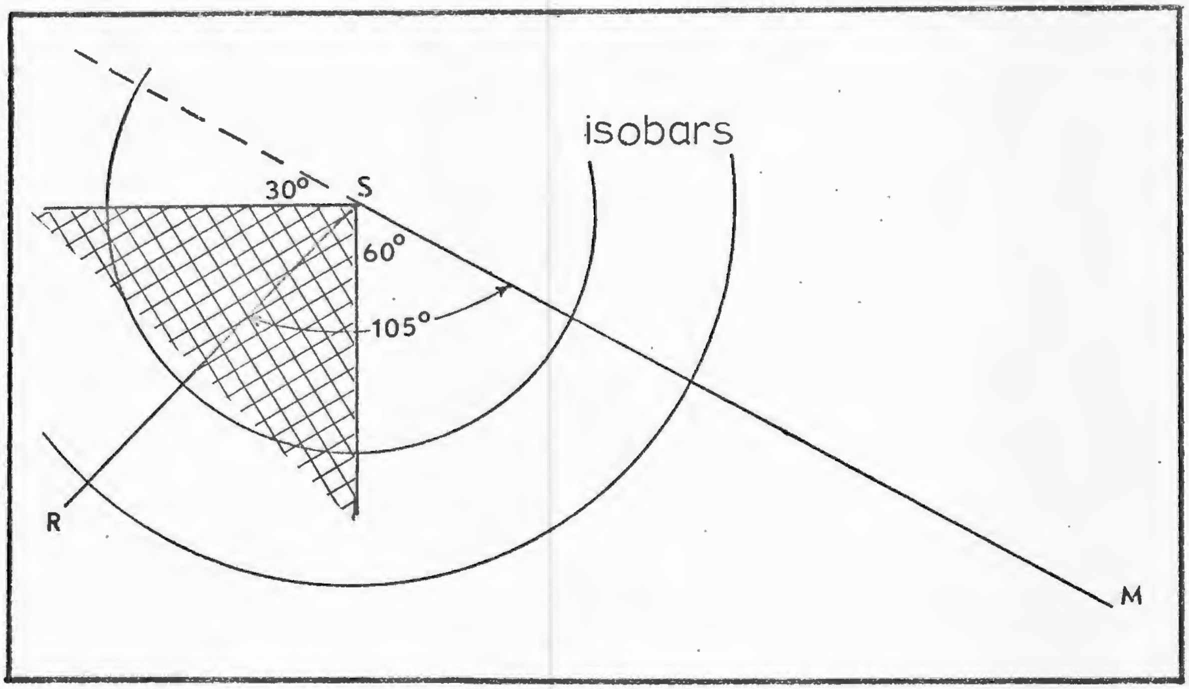


Figure 8b: FINAL DETERMINATION OF THE WIND FIELD BASED ON SURFACE WIND DIRECTION

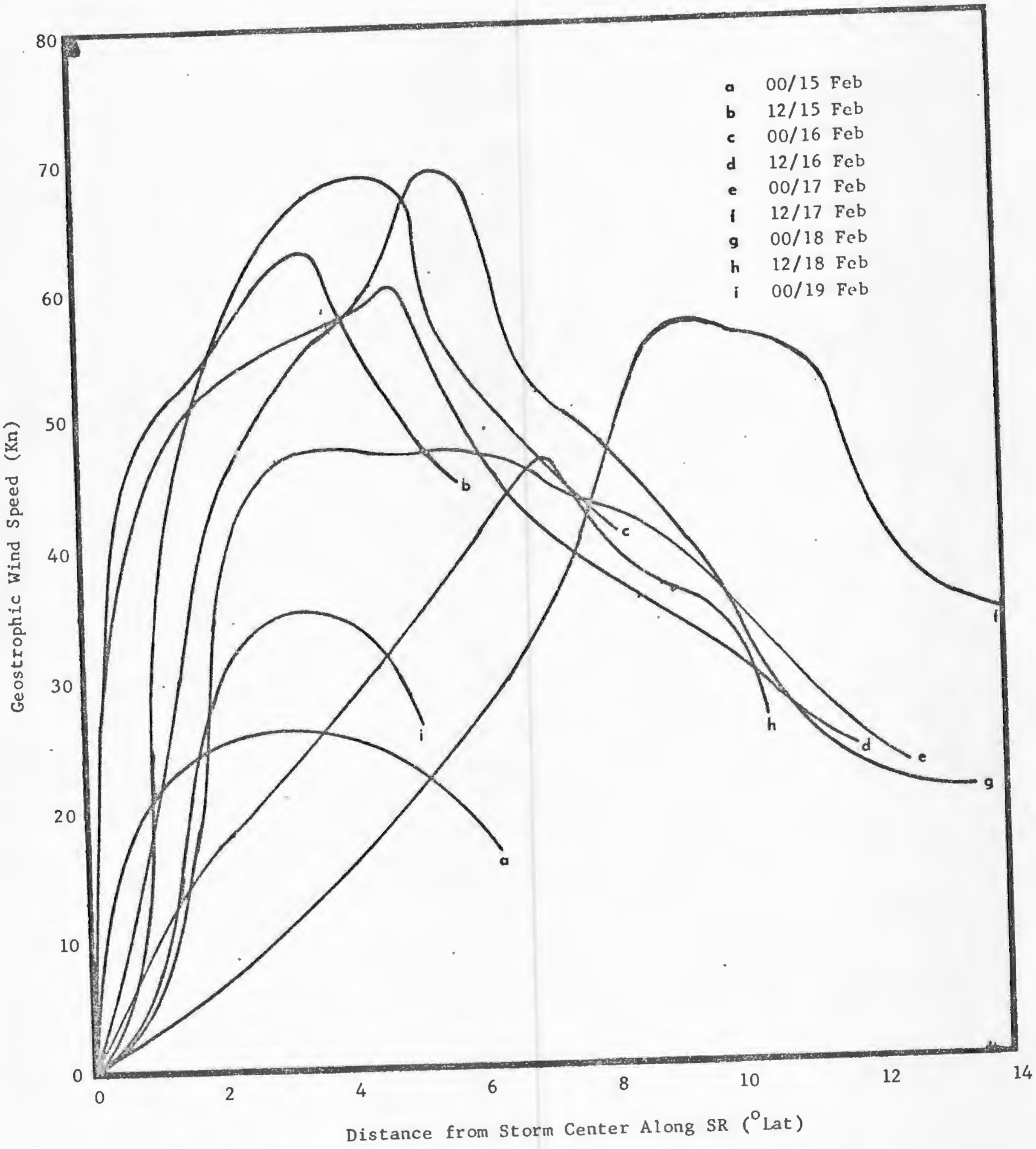


Figure 9: GEOSTROPHIC WIND CROSS SECTIONS; STORM 1

The value of V_g at each midpoint was then plotted against the distance of the midpoint from the storm center to give a graphical cross section of the geostrophic wind speed along the reference line. Figure 9 shows the cross sections, at 12 hour intervals, constructed for Storm 1.

4. Determination of Fetch Reference Point

In drawing each cross section of the geostrophic wind speed, an attempt was made to fit a smooth curve to all the data points. This usually gave acceptable results but, in some cases, singularities existed which may reflect peculiarities inherent in the procedures used in constructing the sea-level analyses. These singularities were ignored in drawing the cross sections.

The peak value of the geostrophic wind along the reference line was felt to have special importance, as it was presumed that the peak energy in each swell set recorded at Monterey was generated at, or in the vicinity of, this peak wind location. The location along SR of this wind, as given in the cross-section graph, was plotted as a point on the weather map. This point was called the reference point and was of major importance in determining many of the parameters associated with the fetch, as will be shown below.

5. Fetch Width

Having determined the general location in which the peak wave energy is considered to have been produced on each weather map, it was desired to quantitatively establish a means of placing lateral limits on this region. It was not known to what degree the peak energy region of the sea approached a fully arisen state; however, it was assumed that the seas along the wind cross section did approximate fully arisen conditions. In order to obtain a measure of the width of the fetch, an energy criterion was established which placed the fetch limits at those points along the reference line where the fully arisen wave energy that would be produced by the wind at those points was a fixed percentage of the fully arisen sea energy that would be produced at the fetch reference point.

In order to select a percentage that would appear to give a realistic fetch width, energy values for a fully arisen sea were obtained for different wind speeds using the Pierson-Neumann-James [1955] energy spectra. This energy was reduced arbitrarily by 70 or 80 per cent, and wind speeds that would be needed to generate fully arisen seas having the resultant energy were determined. The results are shown in Figure 10. Using the 80 per cent energy criterion, almost no reduction in wind speed resulted and the fetch width that resulted was unrealistically narrow. The 70 per cent energy criterion also resulted in only a small reduction in wind speed, but this was sufficient to produce a reasonable value of the fetch width. This criterion was adopted, and the reduced geostrophic wind speed so obtained was used to enter the cross-section curves, on either side of the peak wind, to obtain the locations of the fetch edges, hence the fetch width, along the reference line. This procedure is illustrated in Figure 11.

6. Fetch Length

Determination of the fetch length, F, was the most subjective procedure in the construction of the fetch. The determining factors used in defining the fetch length were the directional criterion for surface winds, the fetch width, and consideration of the curvature and pressure gradient along the isobars. The procedure adopted was as follows.

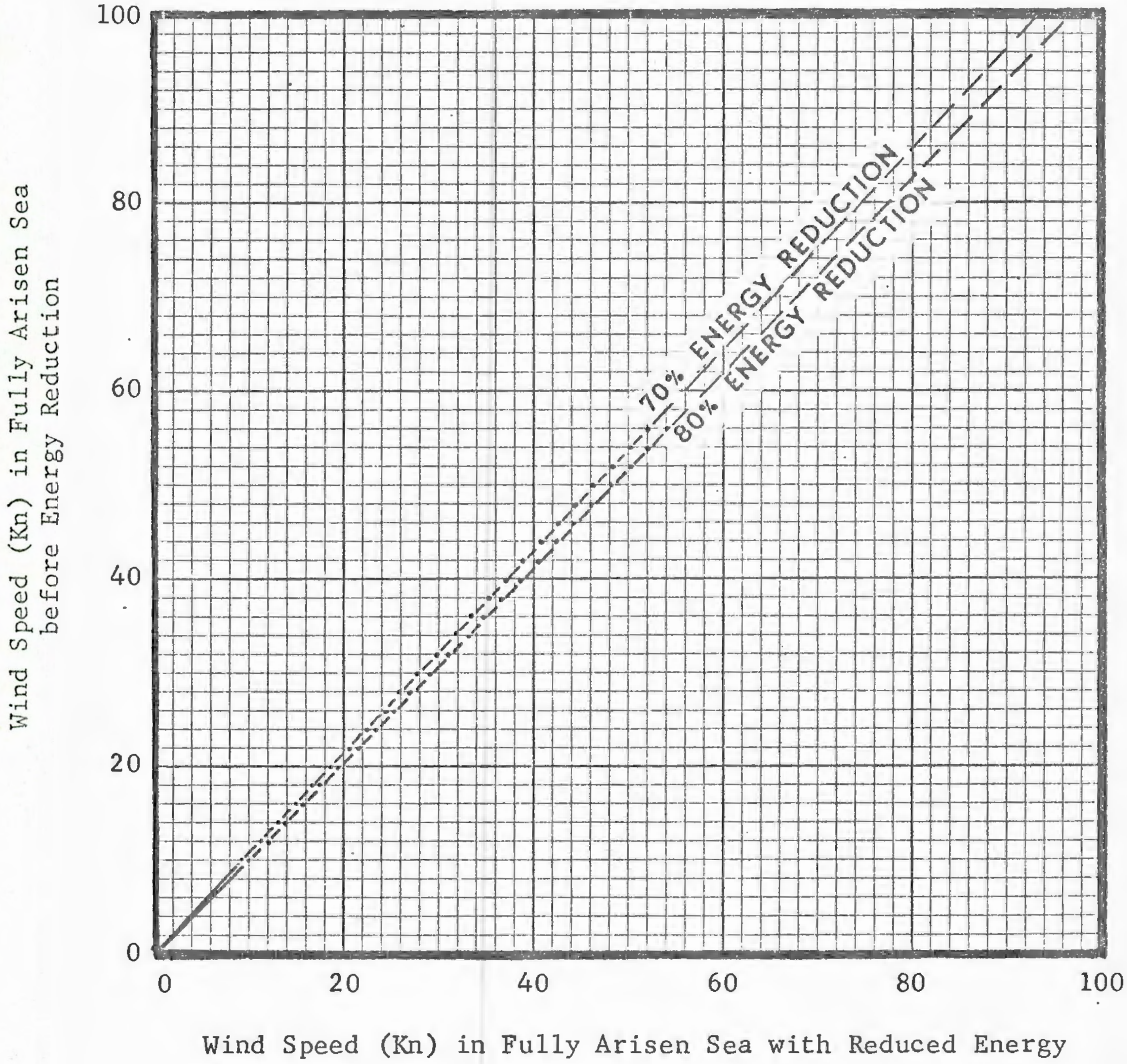


Figure 10: WIND SPEED REDUCTION

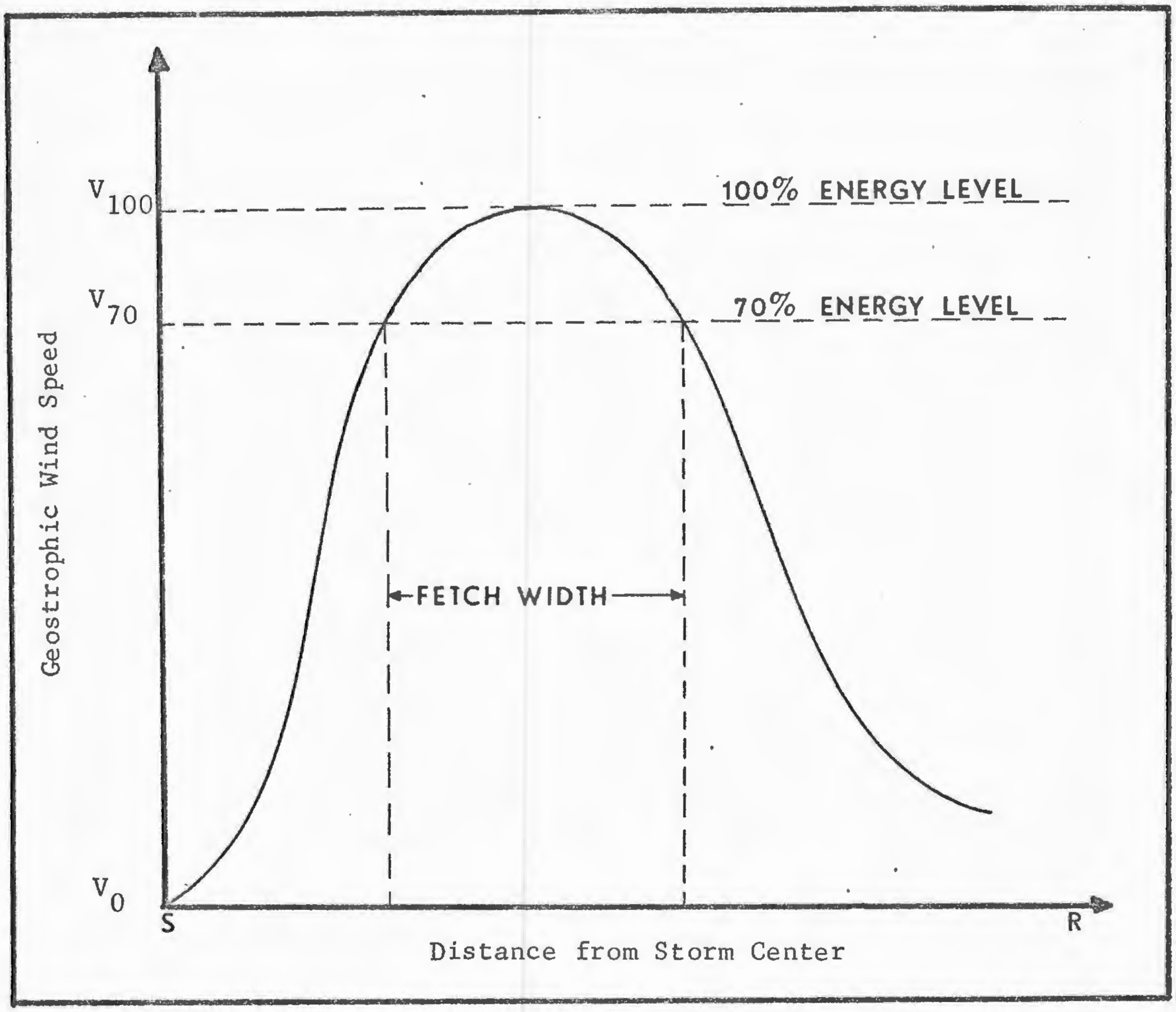


Figure 11: DETERMINATION OF THE FETCH WIDTH FROM GEOSTROPHIC WIND CROSS SECTION

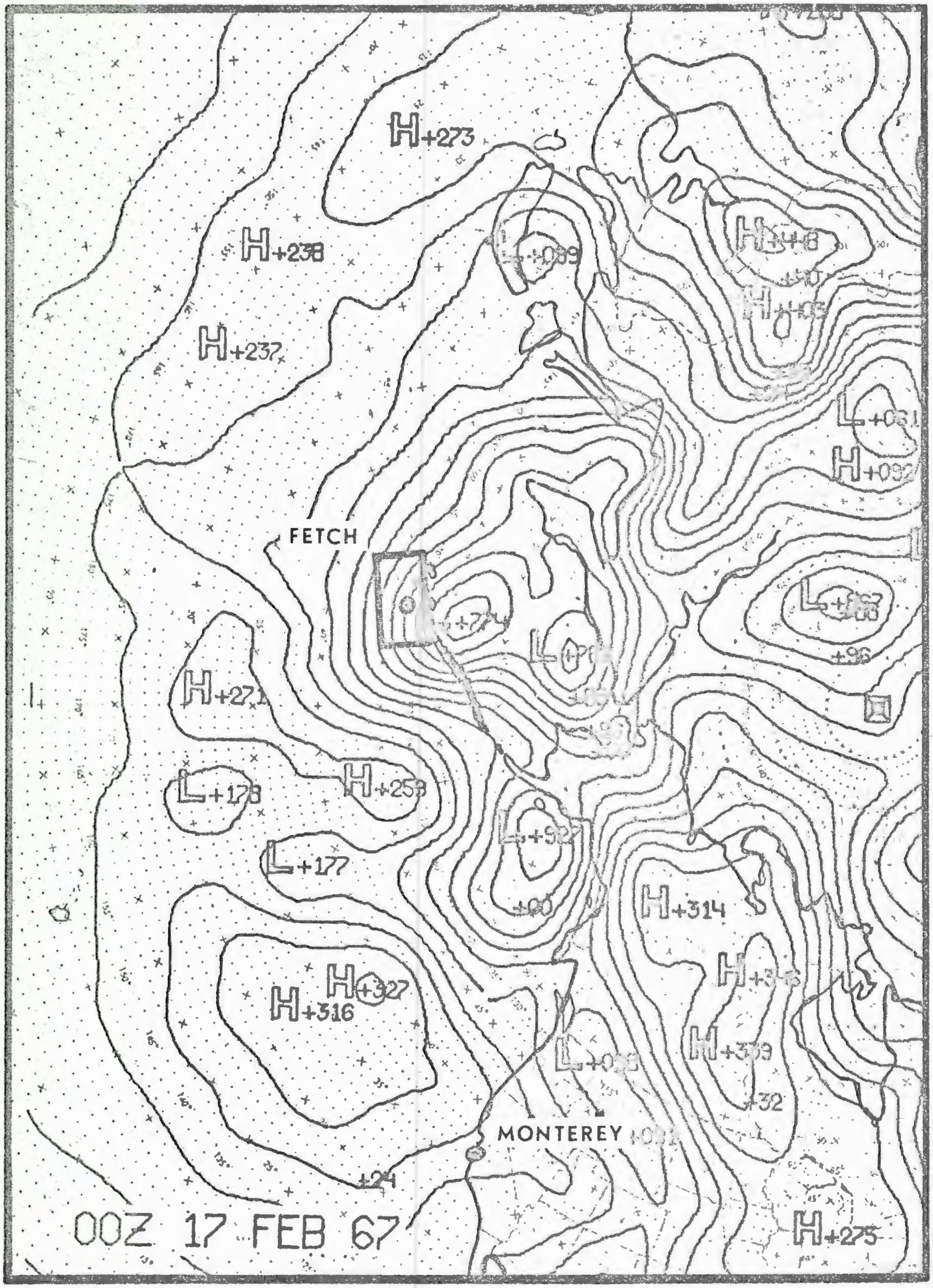


Figure 12: FETCH FOR STORM 1, 00Z/17 FEB 1967

The sides of the fetch were formed by drawing parallel lines in the mean direction of Monterey through the two points on the reference line representing the edges of the fetch. An overlay designed for circular storms was used to determine what portions of the area between these lines met the 45 degree surface wind-direction criterion. It should be noted here that the isobar pattern on most maps was essentially circular, but that for non-circular storms the hatched area in Figure 8b does not usually encompass the entire directionally limited segment. In the final analysis, the positions of the front and rear boundaries of the fetch were determined subjectively on the basis of isobar curvature and decreasing pressure gradient.

An example of a delineated fetch is shown in Figure 12.

C. PRINCIPAL FETCH PARAMETERS

1. Geostrophic Wind Speed

This is the most important fetch parameter derived. It should be noted from the description given above that the value of V_g used in this study is the maximum value obtained from the weather map and not a space-average over the fetch, as is the conventional method for obtaining the wind speed in wave forecasting. The surface wind speed was obtained from the geostrophic wind speed by a procedure to be described later.

2. Fetch Length and Fetch Width

The computation of both of these parameters is described in the preceding paragraphs. The fetch length, F, was obtained in order to construct the distance-time history of each storm with respect to Monterey, and was not used to make sea and swell forecasts in the usual manner. The fetch width, W_F, was used to determine the angular width.

3. Distance to Fetch

The distance from Monterey to the fetch comprised three measurements: the distance to the front edge of the fetch, the distance to the rear edge of the fetch, and the distance to the fetch reference point. The distance, D, to the reference point, hereafter referred to as the decay distance, was the distance used to calculate the fetch velocity and the angular width of the fetch. All three fetch distances were measured directly from the weather maps along a great-circle route from Monterey.

4. Fetch Velocity

The component of the fetch movement directed toward Monterey is of particular importance in this study. This measure, called the fetch velocity, V_F, was determined from the difference in decay distance, D, over the six-hourly interval between maps. It should be noted that the fetch velocity is the velocity of the fetch reference point only and not the velocity of the storm. The directional component of the fetch movement with respect to Monterey is given by the fetch azimuth determined from each weather map. This is discussed below.

5. Azimuth

The azimuth, ψ, of the fetch from Monterey was obtained directly from the weather maps by use of an overlay of great circle lines radiating from Monterey. This angle represents the true bearing from Monterey of the fetch reference point.

6. Angular Width

The angular width of the fetch, α, was calculated from the relationship,

$$\tan \frac{\alpha}{2} = \frac{W_F/2}{D},$$

and represents the angle intercepted by the fetch width when viewed from Monterey.

7. Land-Mass Interference

All but one of the storms studied moved eastward across the North Pacific with the westerly airflow, and eventually crossed the Aleutian Island chain or the Alaska mainland thus markedly reducing or eliminating the effective fetch. The wind-field parameters affected by this interference are the fetch width, the fetch length, and the angular width.

D. SUMMARY OF FETCH PARAMETERS

Figures 13 through 17 graphically present, directly or indirectly, the history of the fetch parameters described above for the storm systems associated with the five swell sets. Considerable variability occurred in some parameters, such as the peak wind speed, accordingly the plotted values are three-point running time means of the calculated parameters. The hatched areas in these figures represent the effects of land-mass interference. A small arrow has been placed on each graph to indicate the apparent origin time of the associated swell set.

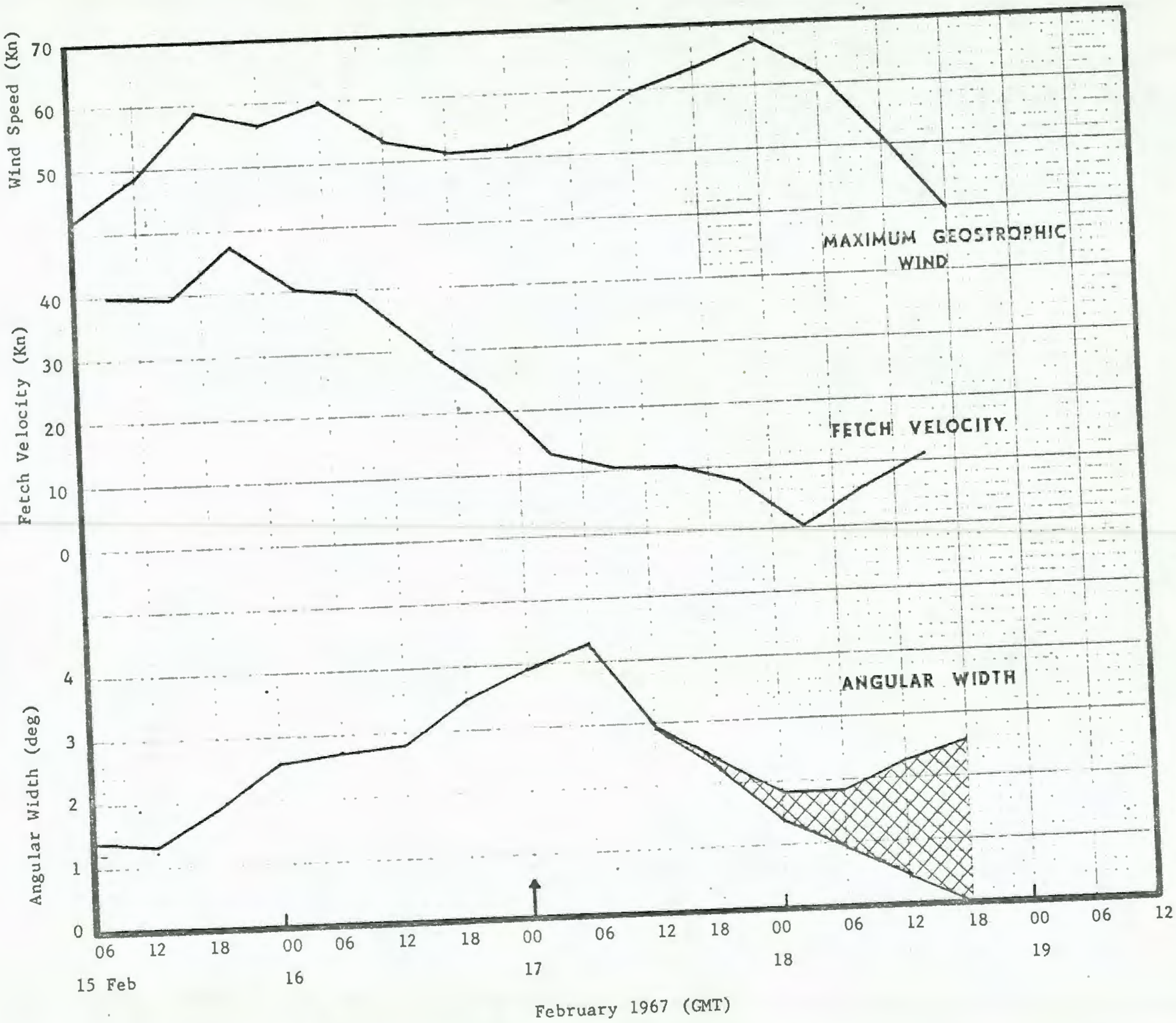


Figure 13a: FETCH PARAMETERS; STORM 1

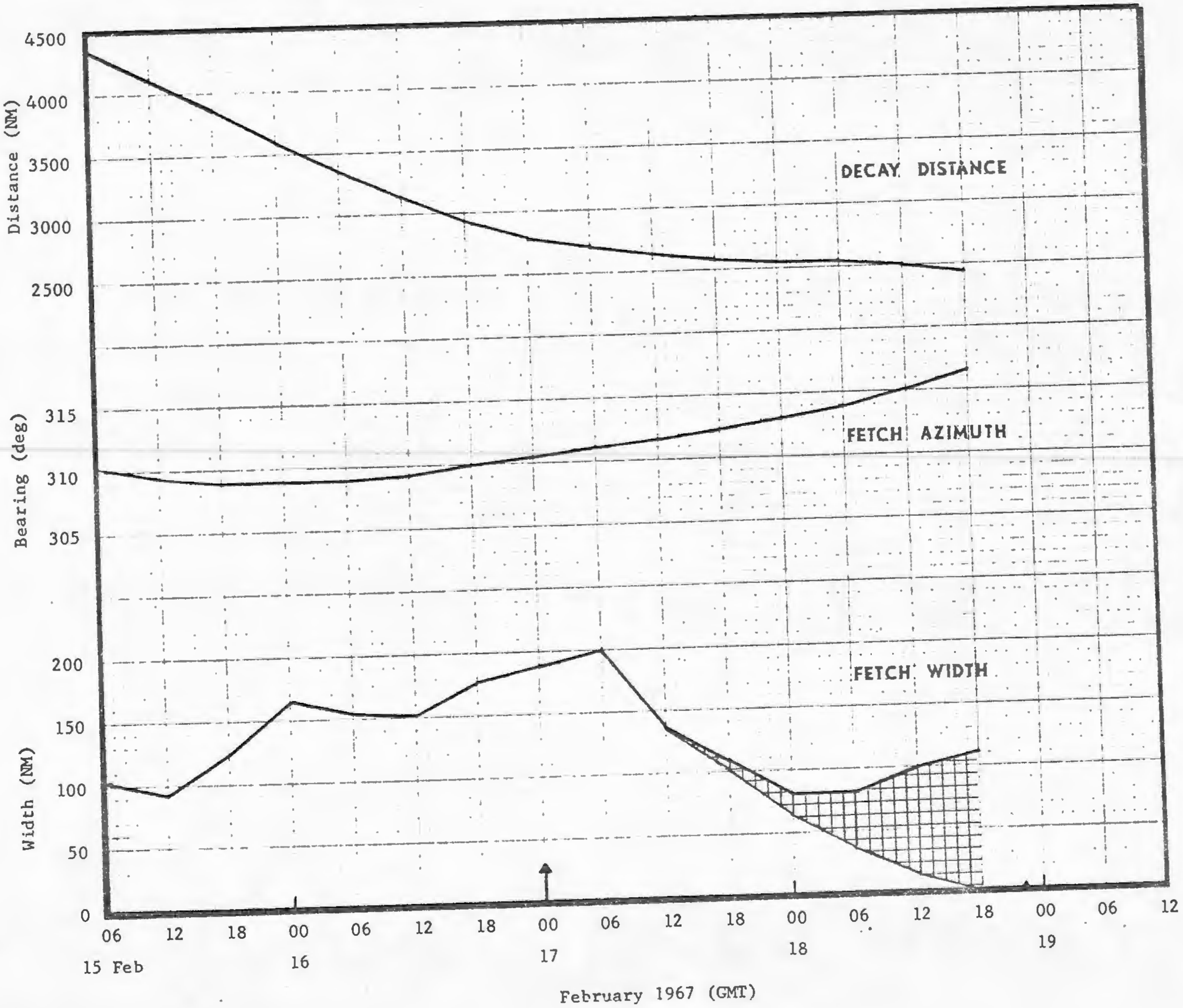


Figure 13b: FETCH PARAMETERS; STORM 1

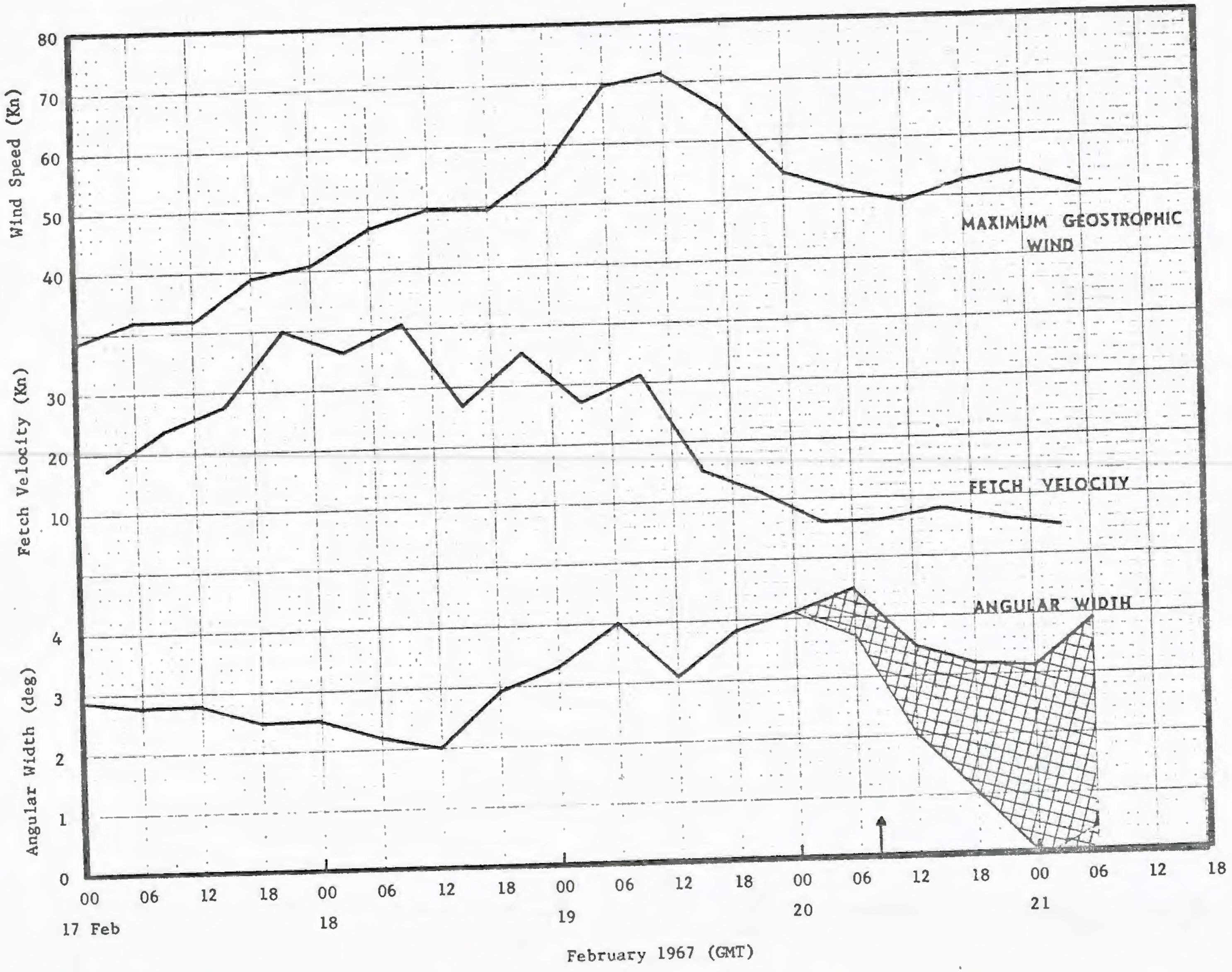


Figure 14a: FETCH PARAMETERS; STORM 2

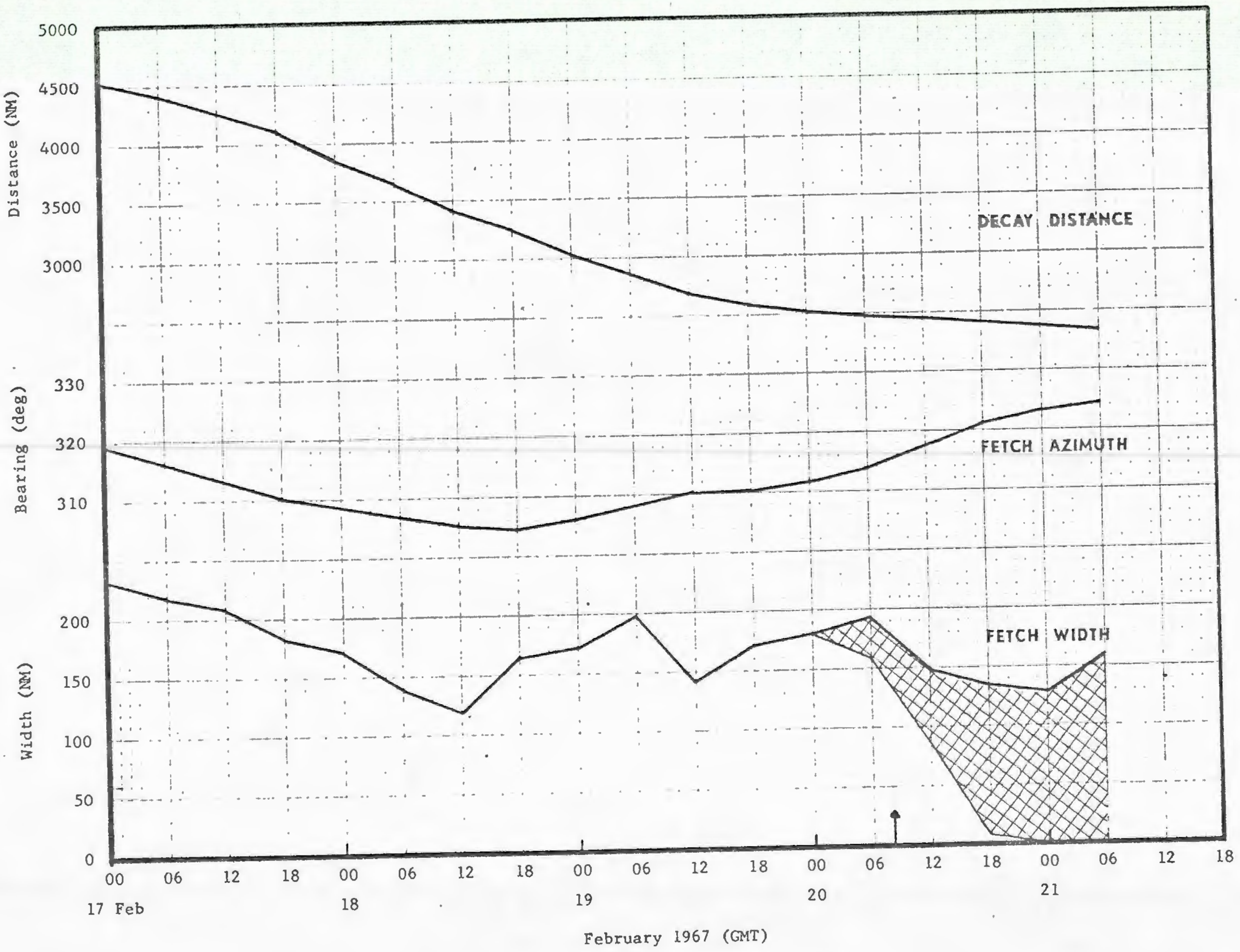


Figure 14b: FETCH PARAMETERS; STORM 2

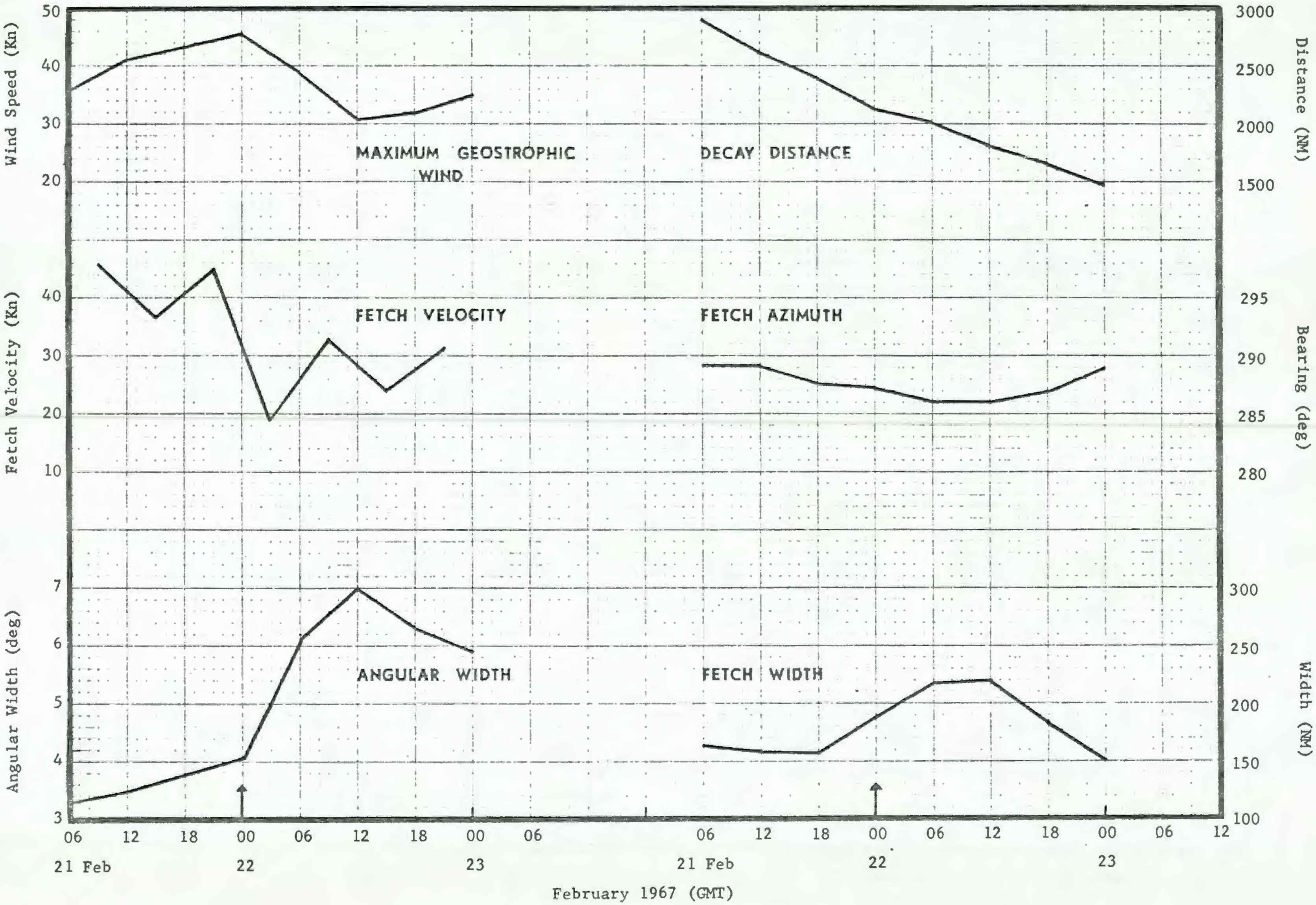


Figure 15: FETCH PARAMETERS; STORM 3A

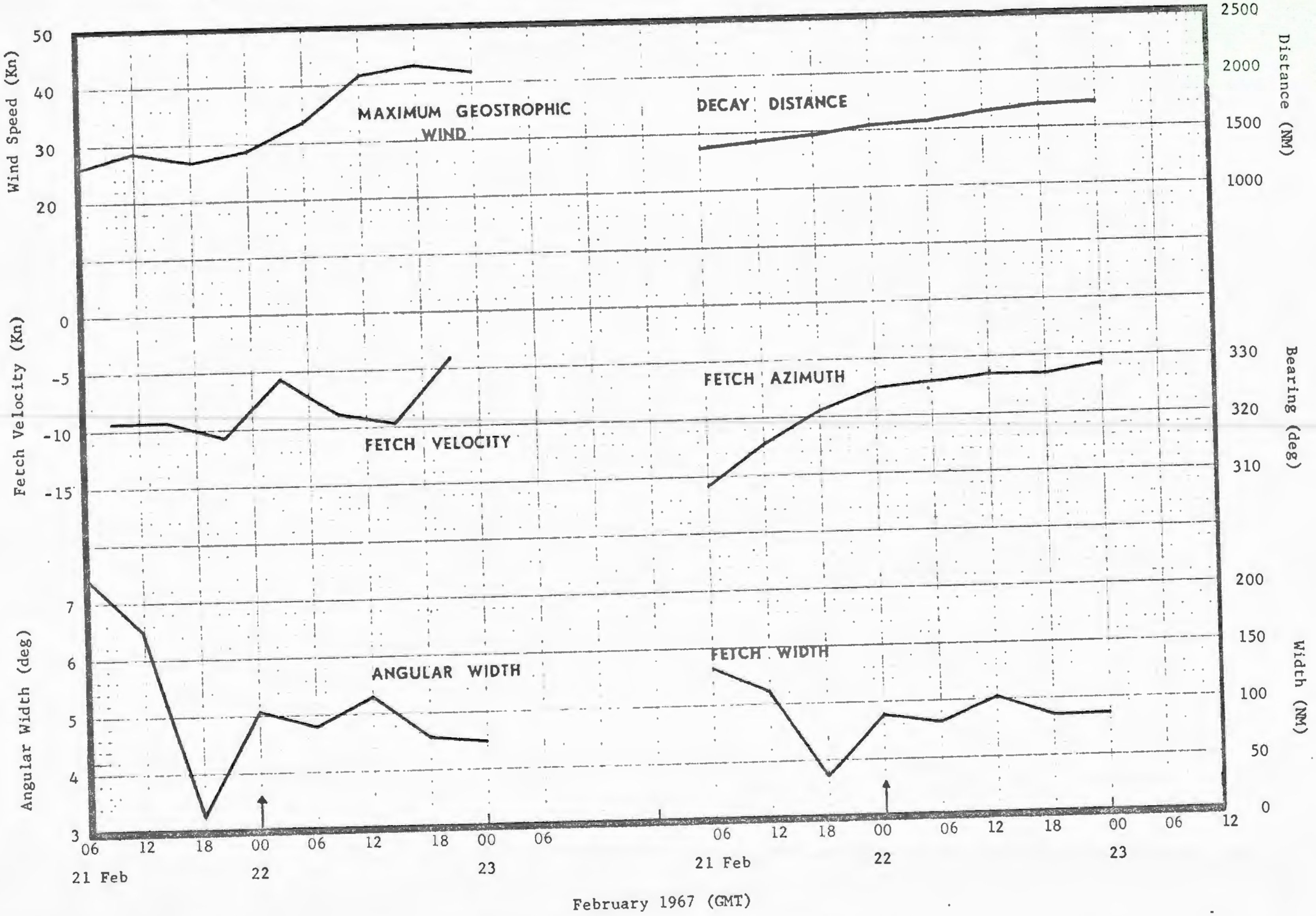


Figure 16: FETCH PARAMETERS; STORM 3B

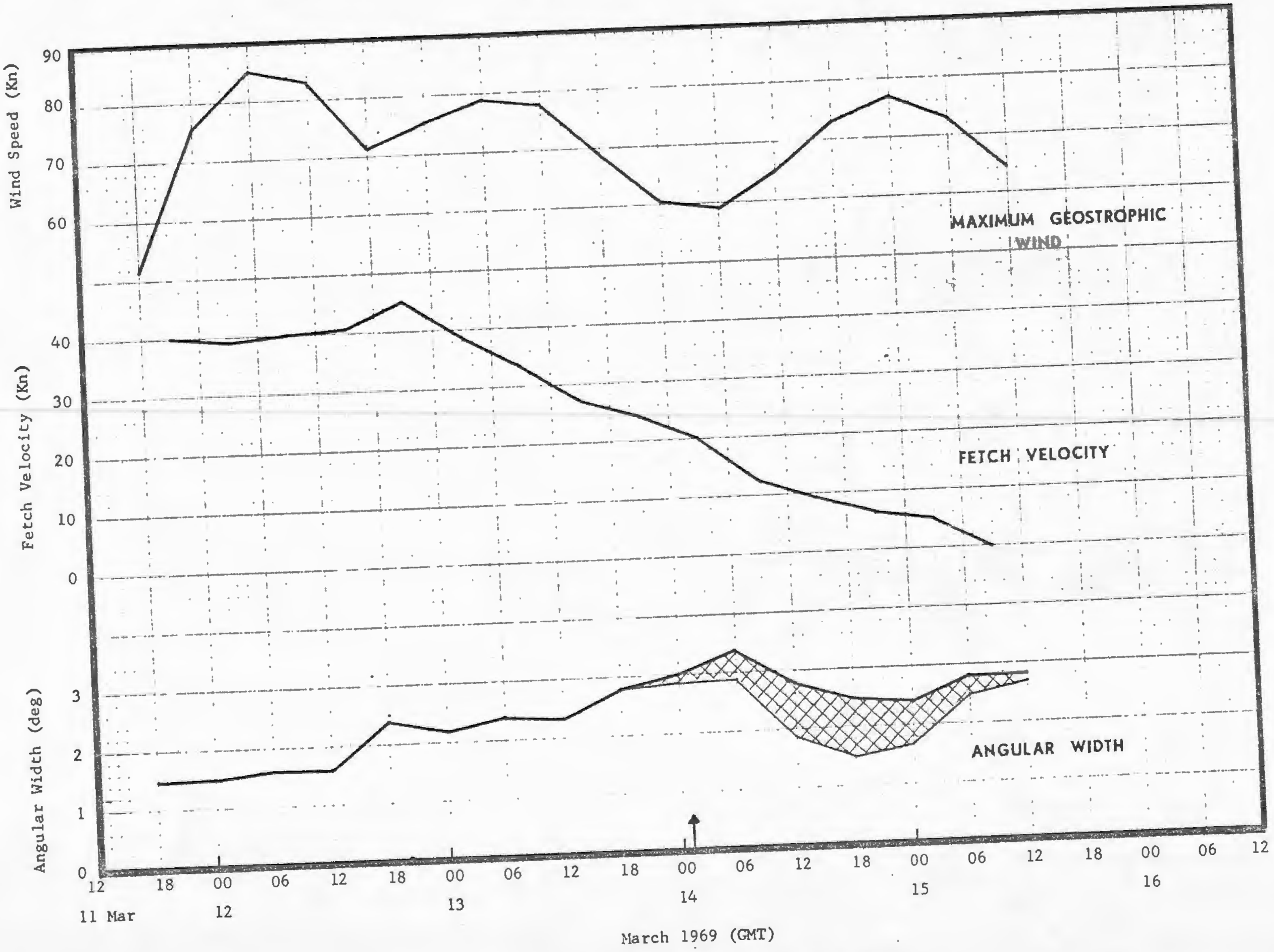
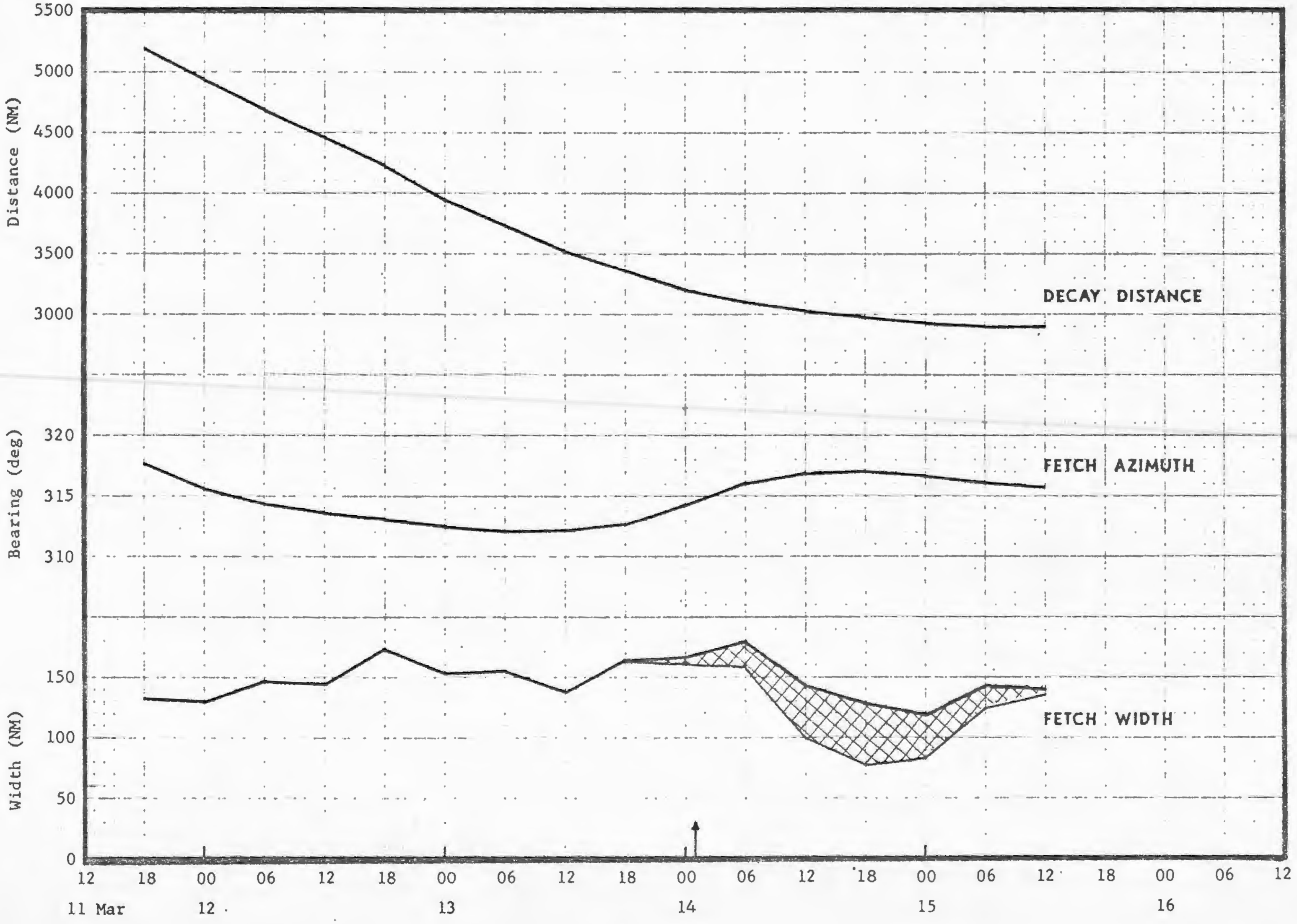


Figure 17a: FETCH PARAMETERS; STORM 4



March 1969 (GMT)

Figure 17b: FETCH PARAMETERS; STORM 4

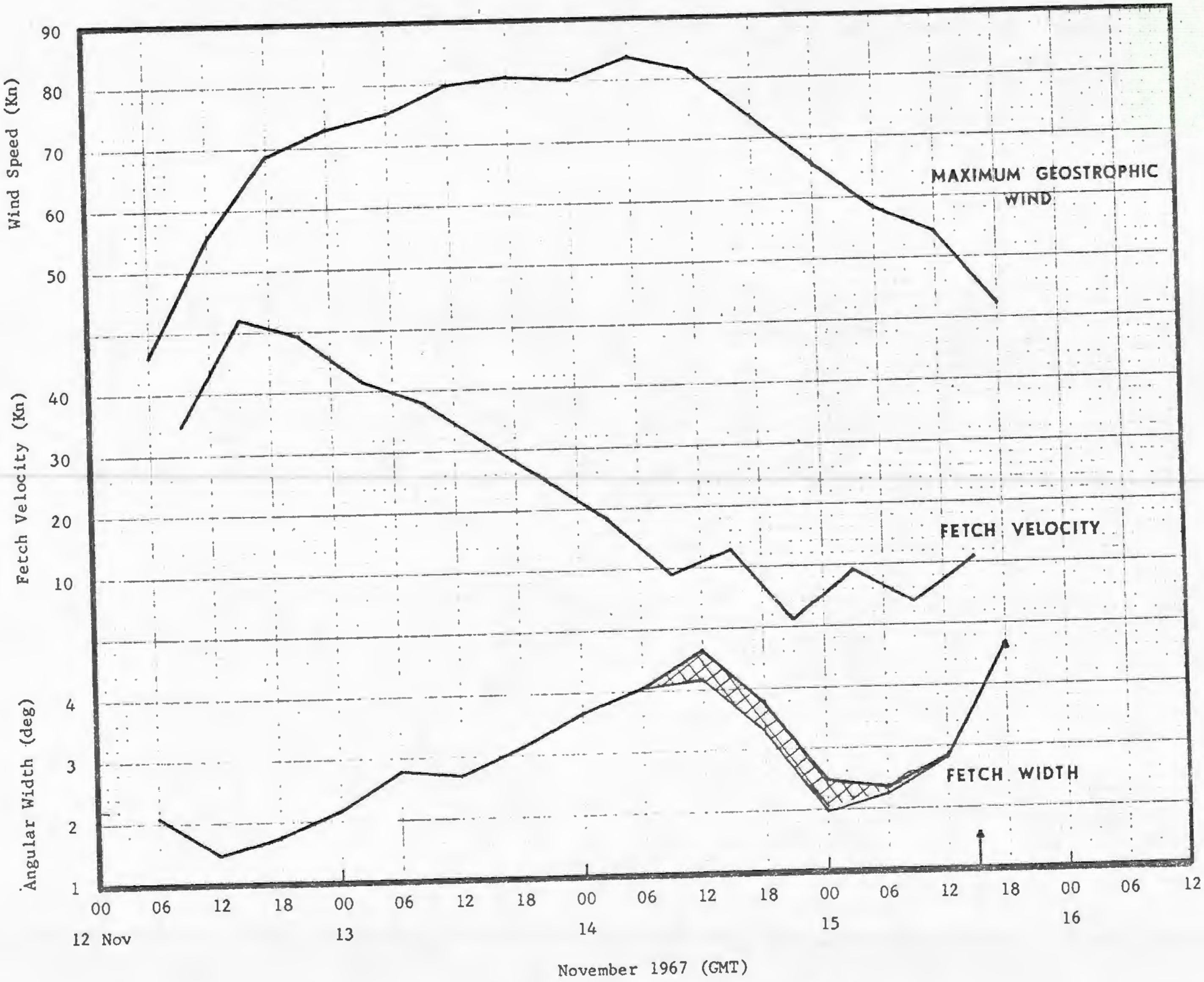
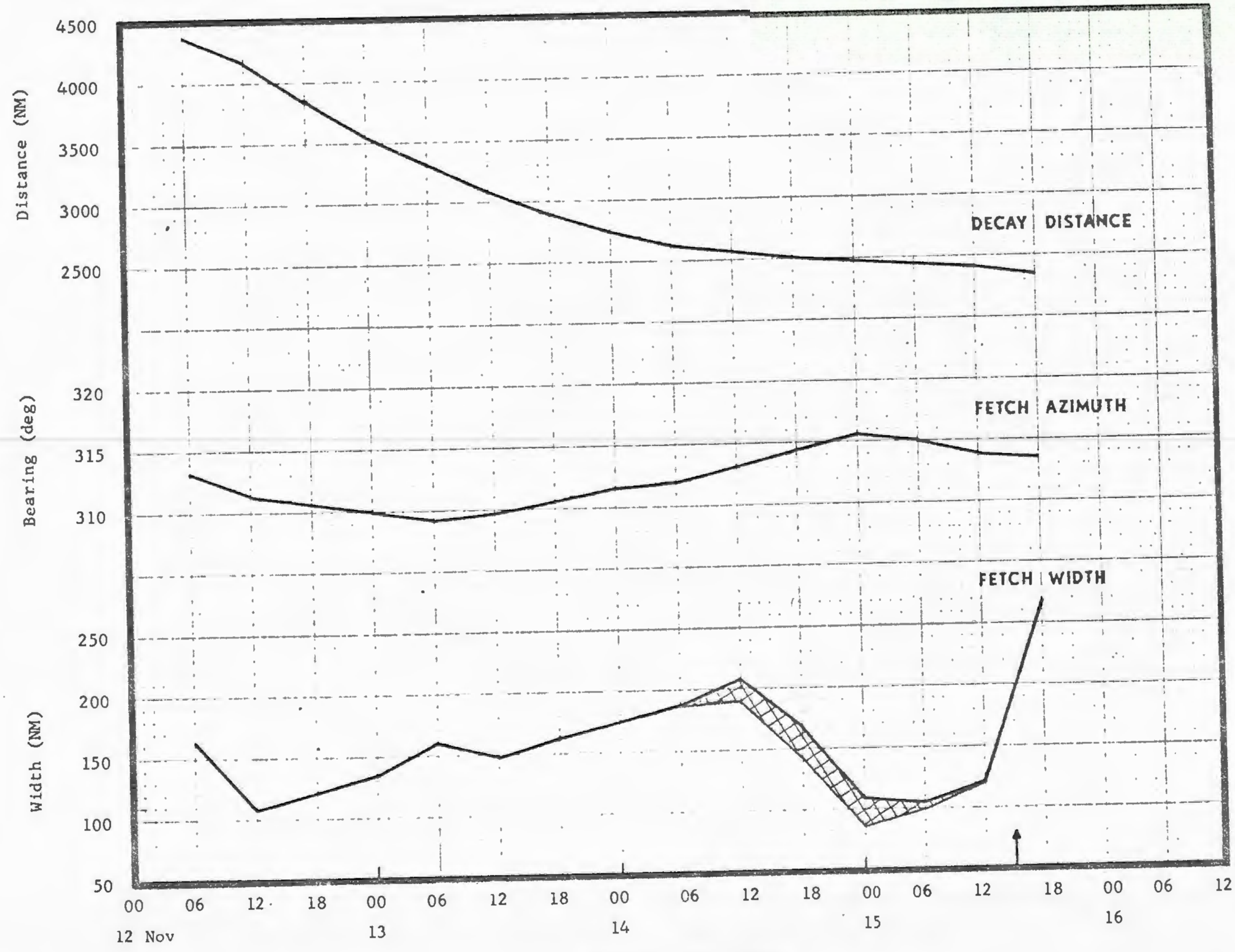


Figure 18a: FETCH PARAMETERS; STORM 5



November 1967 (GMT)

Figure 18b: FETCH PARAMETERS, STORM 5

IV. SWELL ORIGIN IN RELATION TO STORM HISTORY

The principal objective of this study was to determine the conditions prevailing in the wind field at the time and place at which the peak energy in the swell train recorded at Monterey was generated. Four approaches to this problem were taken and are described in this section. None of them involved the forecasting of waves in the fetch or the propagation of swell to Monterey by the conventional methods.

A. FETCH PARAMETERS

The fetch parameters determined in Section III and graphically displayed in Figures 13 through 18 were examined individually for their possible relationship to the apparent source of the swell, which is indicated by a small arrow on the graphs. Fetch length was considered to be unimportant in this analysis, and wind duration was not examined here because it is believed to be reflected indirectly by the fetch velocity.

No single parameter was found to be indicative of the origin of the peak swell energy emerging from a storm. A general statement may be made, however, concerning the five cases studied: the origin time of the swell apparently occurs in the later stages of the storm development, near a time when the fetch velocity is low compared to the velocity in the early stages, and when the angular width is large.

1. Geostrophic Wind

The geostrophic wind histories of the five storms show a fair amount of variability, and in most cases more than one wind maximum occurs in the record. It seems logical that the peak swell energy would be generated by a wind-speed maxima, but the apparent origin times of the swell sets do not coincide with a peak wind value except in the case of Storm 3A. Based on the fetch histories derived in this study, no generalizations concerning the peak swell source can be made solely from the wind record.

2. Decay Distance and Fetch Velocity

The distance from the fetch reference point to Monterey decreased throughout the storm history for each storm studied, except in the case of Storm 3B where the opposite was true. While the decay distance gave no indication of the time of peak swell generation, the time rate of change of this distance, the fetch velocity with respect to Monterey, gave better results. Except for Storm 3B, the fetch velocities for the storms examined were high in the early stages of the storms but decreased considerably during the remaining history. It may be noted that the apparent origin times of the swell were generally in the lower velocity portion of the storm history. In the case of Storm 3B, the negative velocities indicate movement of the swell generating area away from Monterey.

3. Fetch Width and Angular Width

The records of fetch width and angular width for each storm show a good deal of variability, and the apparent origin time of the swell is difficult to relate to these parameters because of this variability, and also because of the effects of land-mass interference. The reduction in width due to the coastal boundary effect is shown by the hatched areas in Figures 13 through 18. More than one maxima occurs in some of the histories, and in several cases a peak width was reduced by land-mass interference. Figures 13 through 18 show that the swell origin time occurred near the time of a peak in the width of each storm. The amount of wave energy propagated to Monterey is governed by the angular width of the fetch, which combines the effects of fetch width and decay distance. The curve of the angular width for each storm is similar to that of fetch width, as would be expected, and diverges slowly with time as the decay distance changes.

4. Azimuth

With the exception of Storm 3B, the swell-generating areas of the storms moved across the North Pacific in slightly curved arcs, as is shown in Figure 19. The total change in the azimuth from Monterey did not exceed 20 degrees for any storm and the changes took place gradually with no abrupt variations. The swell-generating area of Storm 3B differed from the others in that it moved northward along a markedly different path with a fairly rapid increase in azimuth. The apparent origin times of the five swell sets varied from storm to storm with respect to the trends of the azimuth curves as may be seen in Figures 13 through 18, and considered alone, the azimuth information gave no explicit indication of when the peak swell generation occurred.

B. DISTANCE-TIME ANALYSIS

1. Swell-Origin Point

Another procedure for relating the swell characteristics at Monterey to the storm history involved the construction of distance-time (d-t) graphs for each synoptic storm sequence. These graphs are shown in Figures 20 through 25. On each graph, the distances from Monterey to the front edge, rear edge, and reference point of the fetch are plotted against time. The result is a graphical history of the movements of these fetch elements. Also plotted is the point which marks the apparent source of the corresponding swell set as determined from the frequency-time analysis.

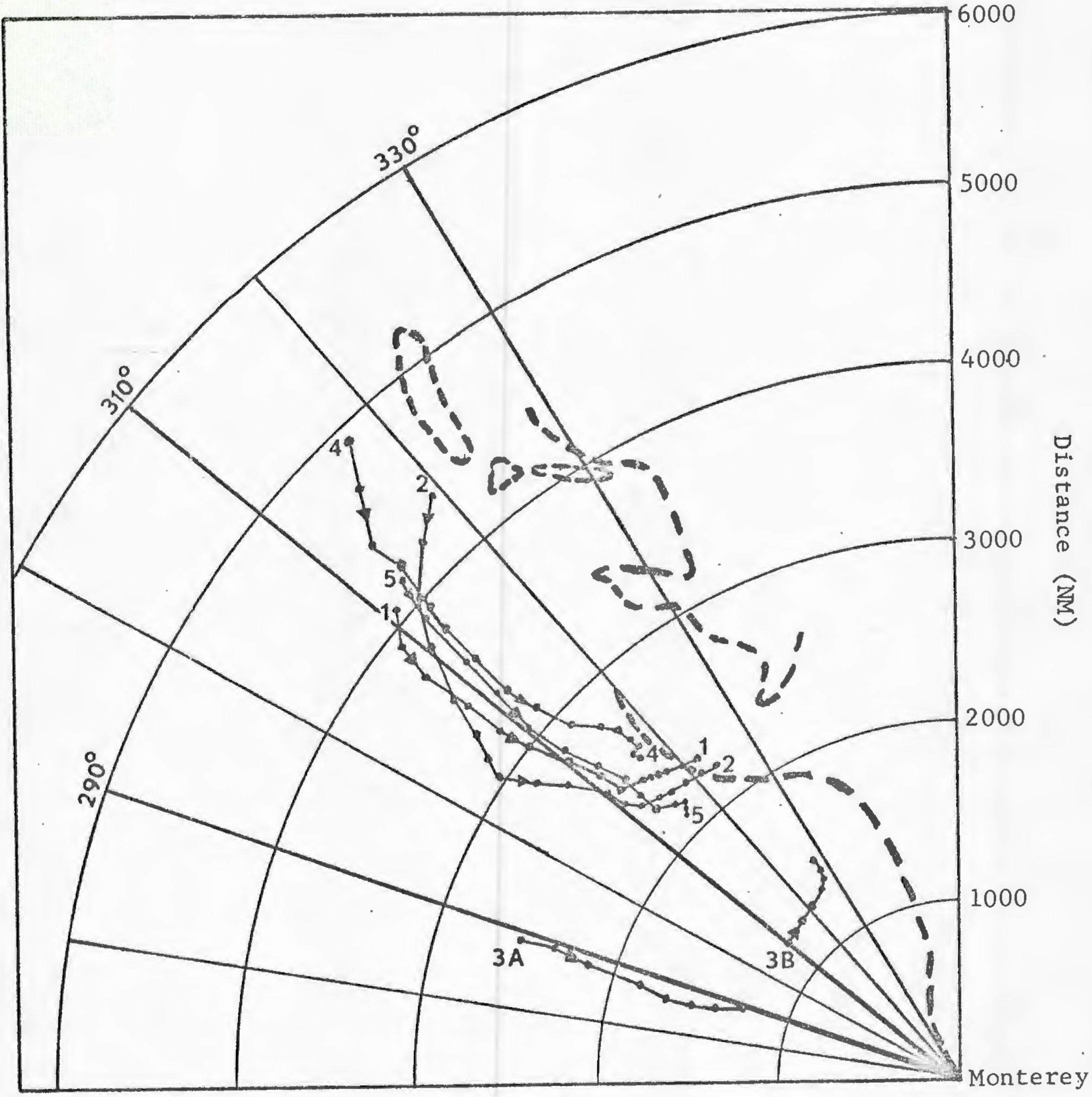


Figure 19: FETCH PATHS WITH RESPECT TO MONTEREY
The dashed lines mark the coastal boundaries.

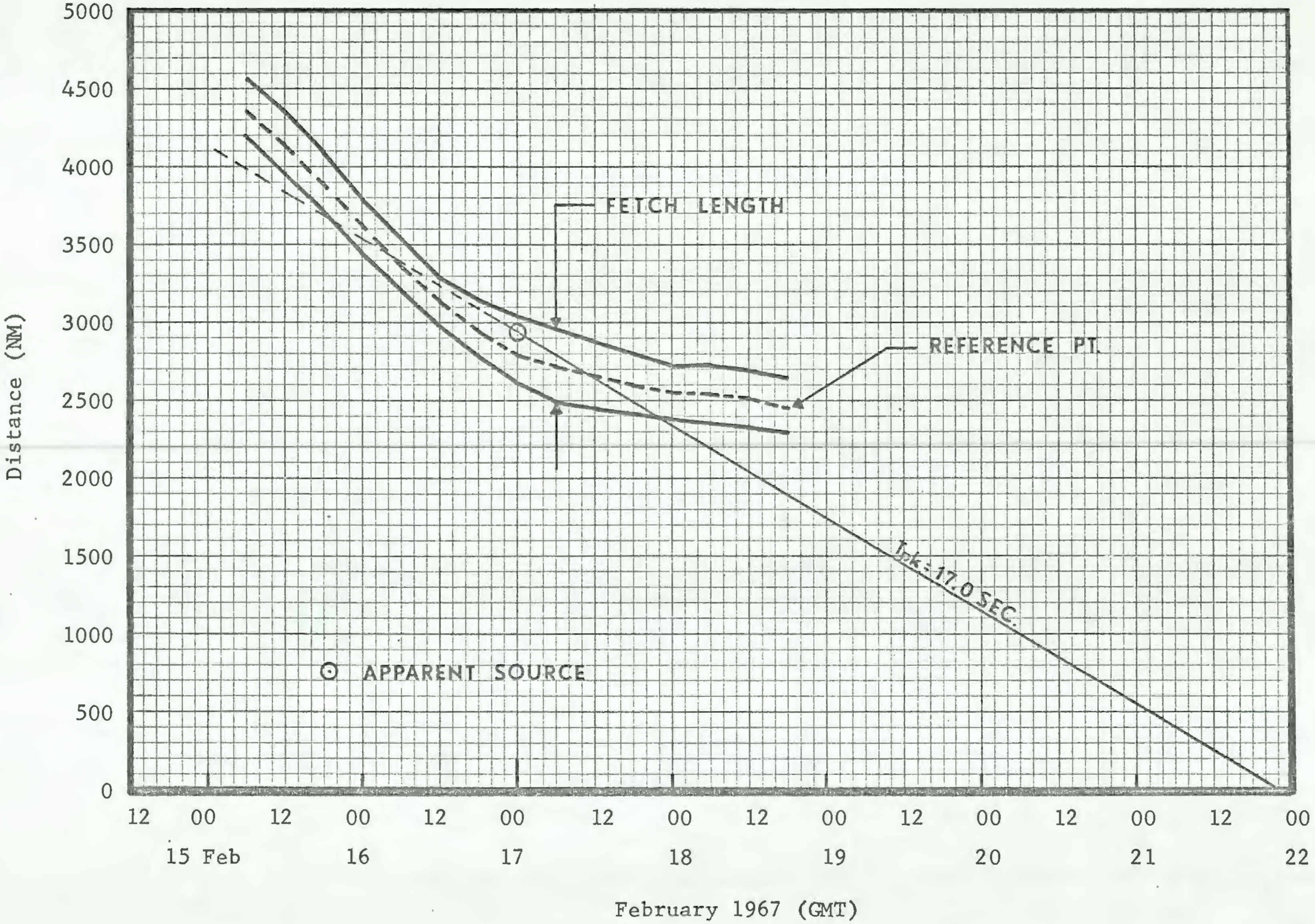


Figure 20: DISTANCE-TIME ANALYSIS; STORM 1

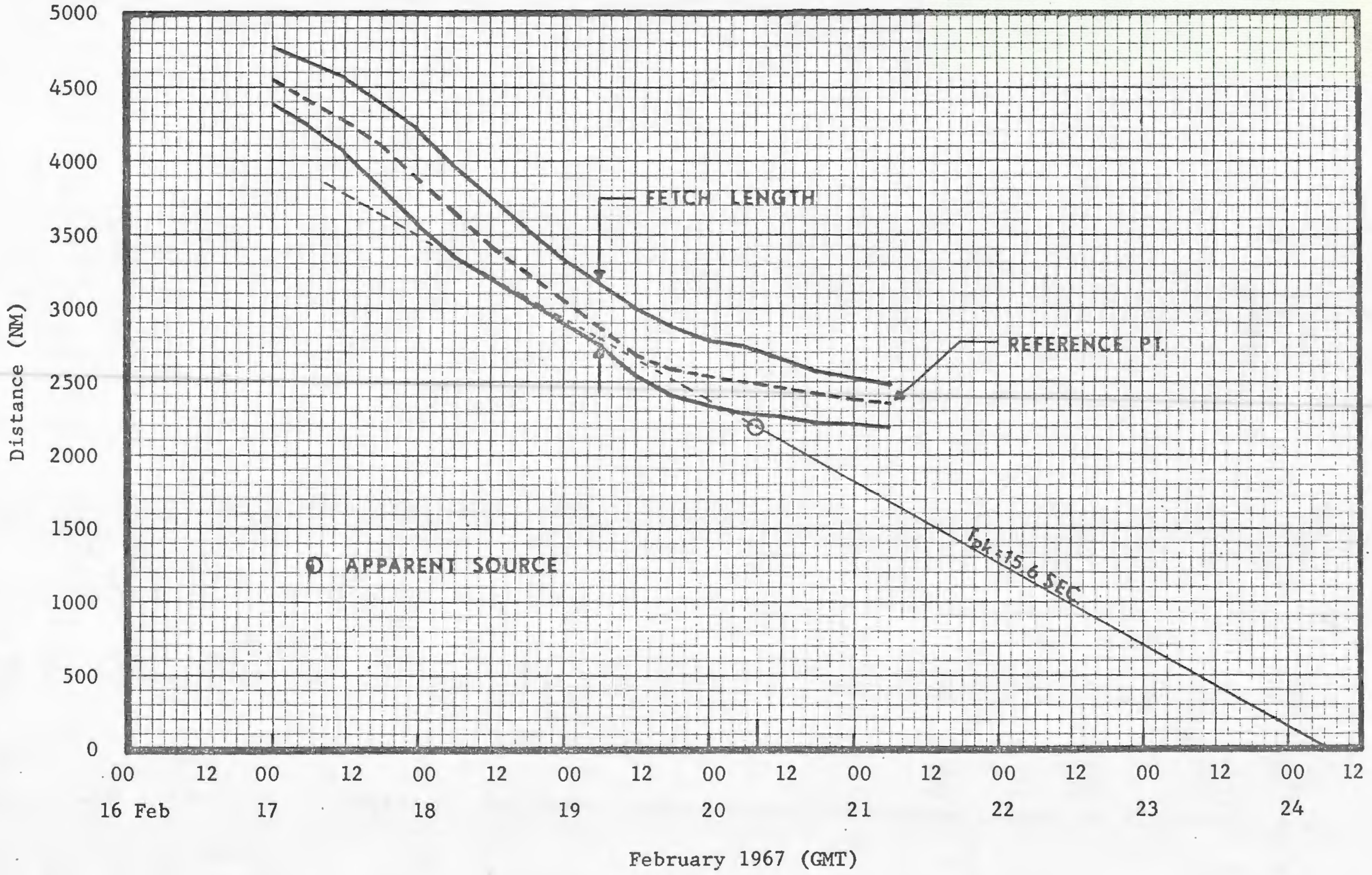


Figure 21: DISTANCE-TIME ANALYSIS; STORM 2

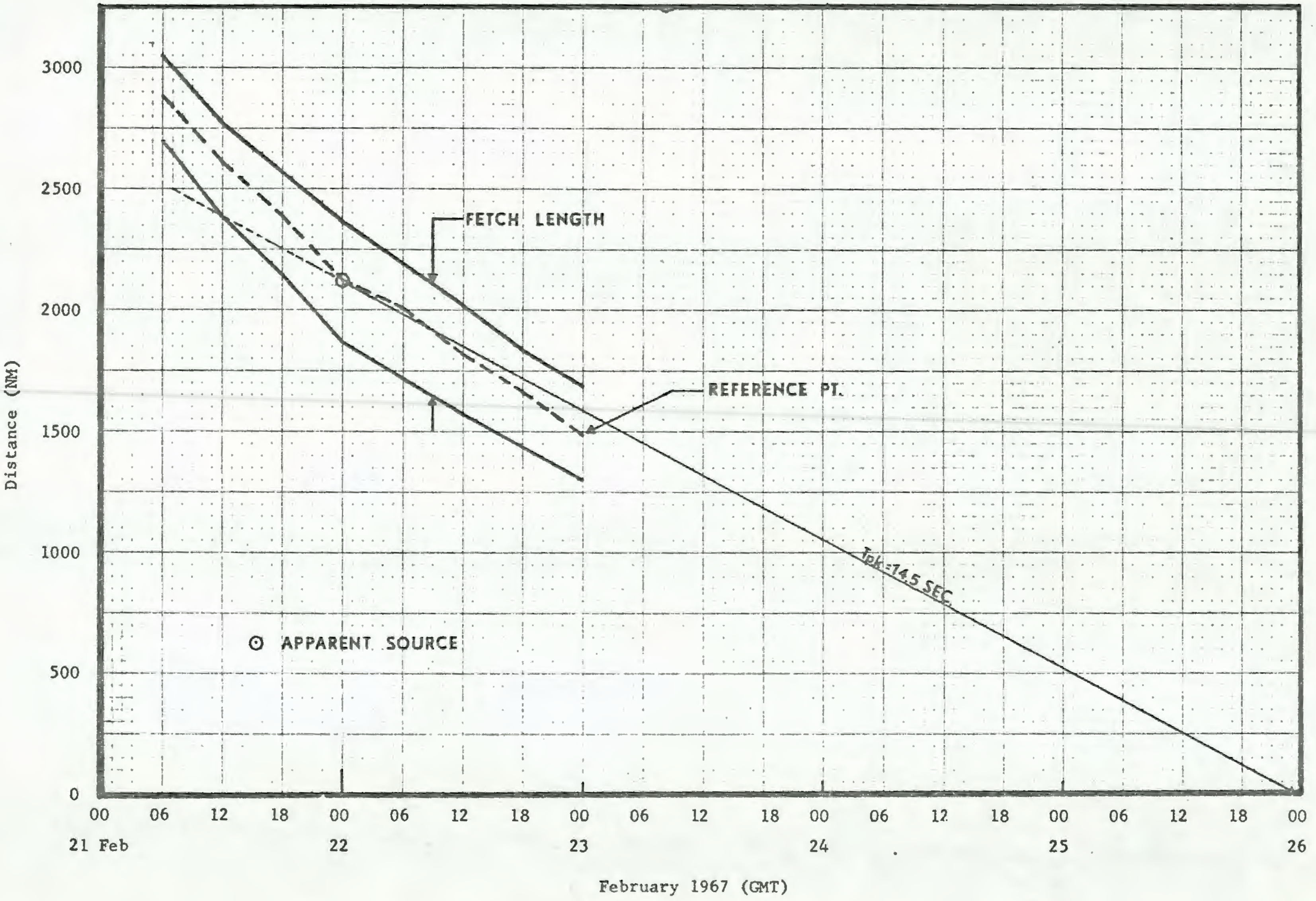


Figure 22: DISTANCE-TIME ANALYSIS; STORM 3A

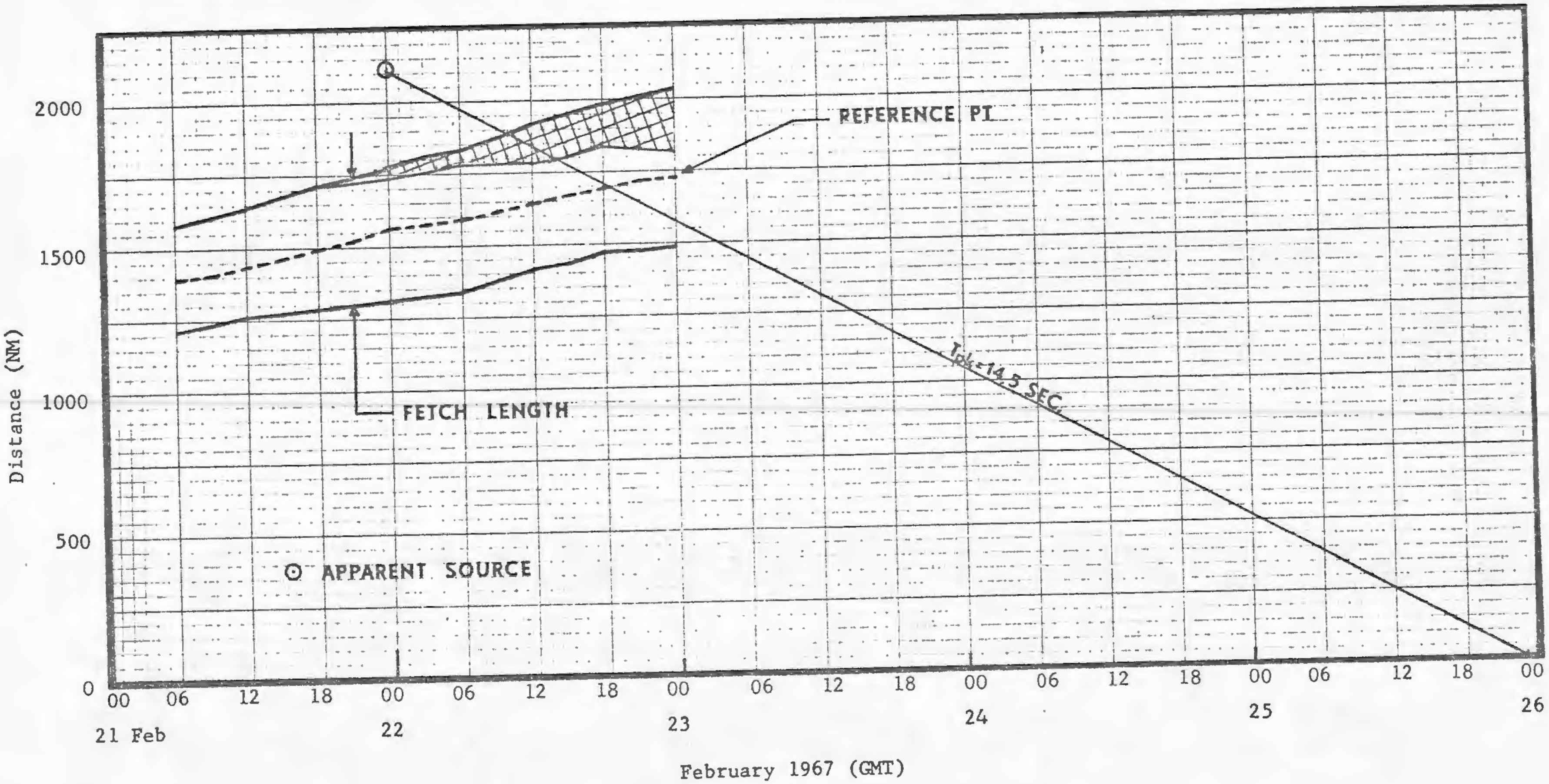


Figure 23: DISTANCE-TIME ANALYSIS; STORM 3B

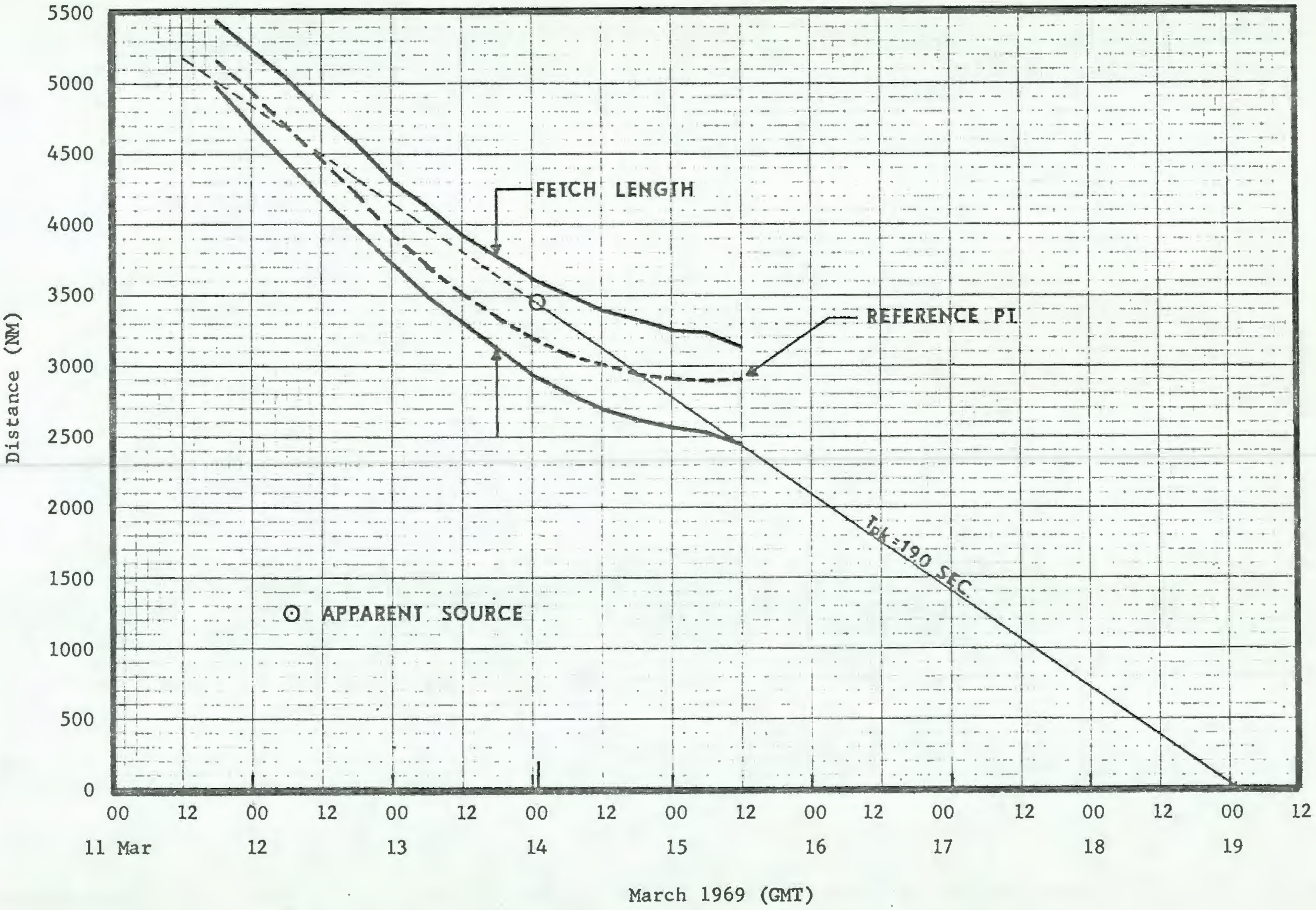


Figure 24: DISTANCE-TIME ANALYSIS; STORM 4

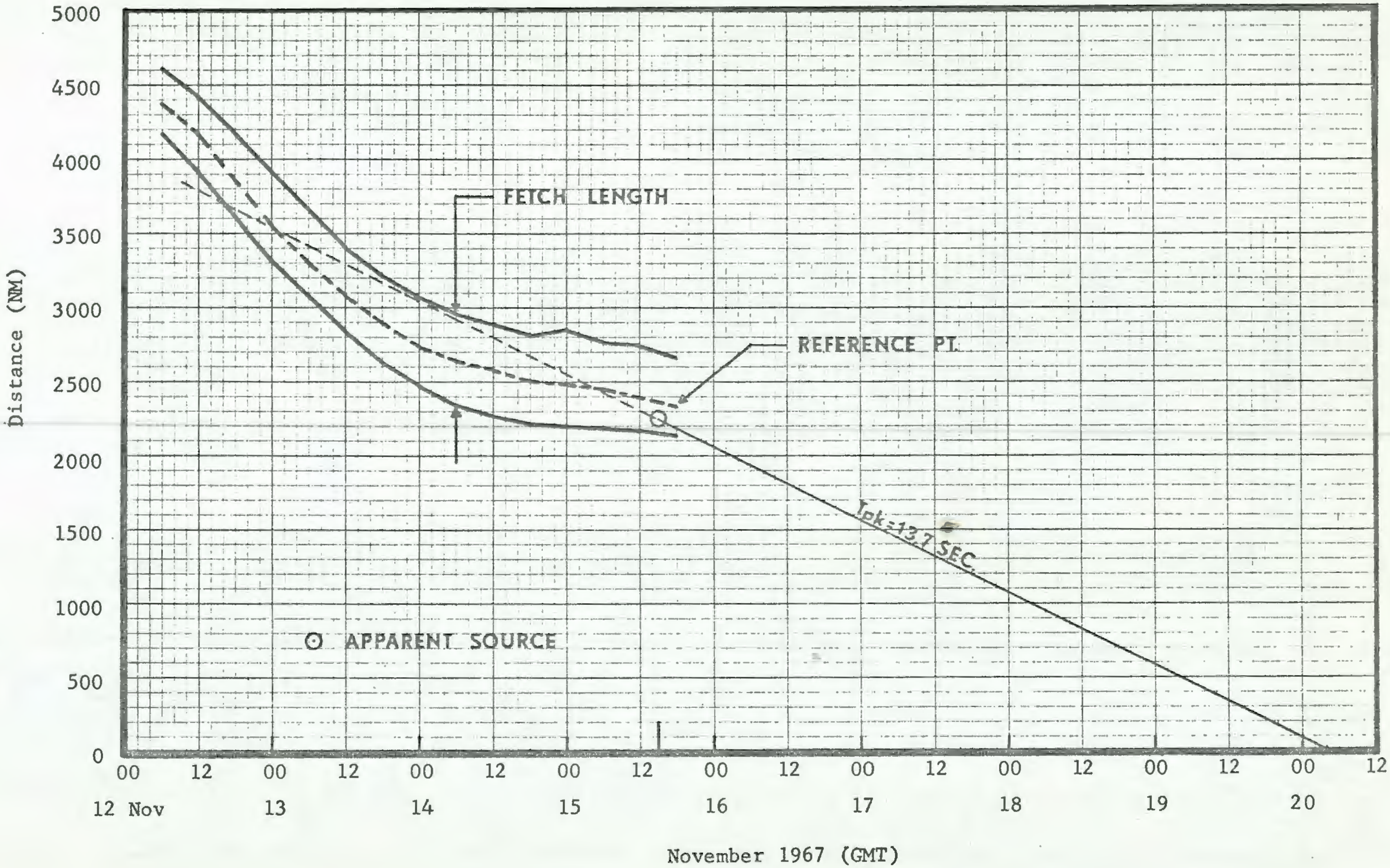


Figure 25: DISTANCE-TIME ANALYSIS; STORM 5

The figures show that, except for Storms 2 and 3B, the apparent swell sources derived from the wave records are located within the fetches developed in this investigation. It should be noted here that the apparent swell cource was derived from the coastal wave records completely independently of the d-t history of the wind field determined for each storm.

For Storm 2, the apparent swell source is located about 50 miles in front of the forward edge of the fetch. The fact that the apparent swell origin for this storm fell outside the wind field may be due to the accuracy of the linear fit to the f-t data (Figure 5). A decrease in slope of the linear fit of only 0.3 cyc/ksec/day would result in an increase of 50 miles in the apparent origin distance. Another explanation for this discrepancy may be that the positioning of the forward edge of the fetch was not satisfactorily determined. While distances can be measured from the surface pressure maps to an accuracy of about 15 miles, the subjective method used to fix the position of the front of the fetch was not precise and the fetch front could easily be 50 miles in error.

The d-t analysis of Storm 3B (Figure 23), which is one of two possible sources of Swell Set 3, exhibits a great discrepancy between the apparent source of Swell Set 3 and the position of the fetch at the apparent origin time. The error is on the order of 750 miles and cannot be explained in terms of errors in the f-t analysis or errors in locating the boundaries of the fetch. In fact, if the swell source was at the distance indicated in the d-t graph and in the same direction as the fetch, it would lie over the Alaska mainland. Because of this discrepancy, Storm 3B was eliminated as the source of Swell Set 3.

The d-t analyses revealed variations in the location of the apparent source within the fetch boundaries. For Storms 1 and 4, the apparent origins of the swell lie near the rear of the fetch, while for Storms 2 and 5, the origin points are located near the fetch front. In the case of Storm 3A, the apparent origin point coincides with the fetch reference point.

2. Fetch Velocity

A useful characteristic of the distance-time graph is that the slope of any line drawn on the graph is a velocity. Thus the slopes of the fetch curves in Figures 18 through 23 indicate the speed of the fetch in the direction of Monterey. With the exception of Storm 3B, each of the storms studied was characterized by high fetch velocities in the early stages of the storm history and low velocities in the later stages. The transition from high to low velocities may be observed in the d-t figures as a distinct change in the slope of the curves.

An interesting observation is that the apparent origin points of the swell originating in Storms 1, 2, 3A, and 4 lie within or close to the zone of fetch-velocity transition. On the d-t graph for Storm 5, however, the apparent source of the swell occurred perhaps a day after the fetch-velocity transition. It should be noted here that an initial f-t analysis of Swell Set 5 was performed in which the linear fit gave an apparent origin at 3300 nm from Monterey at 0800/13 Nov. This positioned the origin point approximately a day in advance of the fetch-velocity transition. This linear fit was judged to be incorrect and a new fit was selected which resulted in the apparent origin time and distance adopted for this study and which is plotted in Figure 25. It may be that the revised fit to the wave frequency data is no better than the original one, and that an intermediate fit might result in the apparent origin point lying close to the fetch velocity transition zone on the d-t graph.

The variability of the apparent swell origin point within the fetch, which was pointed out in the previous section, appears to be related to the fetch velocity. It may be noted that Storms 1 and 4, in which the origin point is located near the fetch rear, are moving rapdily toward Monterey at the time of swell origin, and that Storms 2 and 5, in which the origin point is located near the fetch front, are moving considerably more slowly toward Monterey at the time of swell origin. In the case of Storm 3A, the origin point lies midway in the fetch at the time the storm passed through the velocity transition. This apparent relationship between the location of the swell origin point and the velocity of the fetch may be explained by the consideration that when a wind field travels over the ocean at high speeds (in excess of the group velocity of the waves generated), the largest seas are generated at or near the rear of the fetch; whereas, when a wind field travels slowly (in relation to the group velocity of the waves generated) or is stationary, the largest seas are generated at or near the front of the fetch. It is apparent that at some stage in the deceleration of a rapidly moving fetch the zone of largest seas moves through the wind field from the rear to the front portion of the fetch.

3. Period of the Peak-Energy Swell

The distance-time graphs (Figures 20 through 25) were also used to examine the relationship between the movement of the fetch and the period of the swell energy peak arriving at Monterey. The arrival time at Monterey of the energy peak of each swell set (Table I) was marked on the time axis of the d-t graph. The line drawn on the d-t graph, connecting the swell origin and arrival times, is labeled for the period of the peak swell energy, T_{pk}, observed at Monterey. Its slope represents the group velocity at which the peak energy was propagated toward Monterey. The swell origin point thus represents the apparent source of the peak swell energy in space and time.

The relationship between the group velocity of the peak swell energy and the velocity of the fetch can be seen by comparing the slope of the T_{pk} line with the slopes of the lines representing the fetch movement. It may be noted in the figures that, except for Storm 3B, the T_{pk} lines on the d-t graphs parallel the fetch track in the fetch velocity transition zone in every case, i.e., the group velocity of the peak swell travelling toward Monterey equals the fetch velocity about the time of fetch-speed transition. This observation provides another clue to the relationship between the velocity of the fetch and the location of the source of the peak swell energy. This relationship is explored in greater detail in the following sections.

C. FETCH VELOCITY VERSUS WAVE GROUP VELOCITY

1. Fetch Velocity as a Measure of Duration

A basic factor in all modern wave forecasting techniques is the length of time the wind has blown over an area of ocean. In the forward-moving fetch situation, with which this study is concerned, it is the wind duration rather than the length of the fetch that ordinarily determines the wave energy produced in the sea. In this study, the wind duration was not among the parameters reviewed above; however, an effective measure of the time available for the buildup of energy in the fetch area is the fetch velocity.

As the wave energy in the fetch builds up with time, higher energy waves having larger group velocities are generated. Whether or not these waves remain in the fetch area, thereby increasing the length of time the wind is able to transfer energy to the water, depends a great deal upon the velocity of the fetch. If the fetch velocity is much higher than the group velocity of the peak wave energy being produced, the fetch will leave these waves behind. On the other hand, if the fetch velocity is much lower than the group velocity of the peak energy waves, these waves will run out ahead of the fetch. In either case the peak energy in the sea produced by strong winds is likely to be less than that which would be generated if the waves had continued to be acted upon by the wind for a longer duration. The ideal situation for developing waves of maximum energy would exist if the fetch velocity equalled the group velocity of the peak energy waves. The latter would increase with time, of course, with the growth of the sea. Obviously, the fetch velocity plays an important part in determining the energy level and therefore the peak energy period developed in the fetch area.

In view of these considerations, one important observation that was made is that the characteristics of Storm 3B are markedly different from those of the other storms considered. It has already been noted in the case of Storm 3B (Figure 23) that the discrepancy between the apparent origin distance of the swell, derived from the coastal wave data, and the distance to the fetch, measured from the weather maps, was a major reason for dismissing this storm as the source of Swell Set 3. Another reason for this decision was based on the velocity considerations just discussed. Throughout the observed history of Storm 3B, the fetch was moving away from Monterey. This movement is believed not able to allow a significant energy buildup in the fetch because of the apparent short wind duration. Therefore it is believed that it must have been Storm 3A rather than Storm 3B that produced Swell Set 3.

2. Fetch Velocity and Velocity of Peak Wave Energy

It was noted from the d-t analyses (Figures 20 through 25) that the apparent swell sources are located at or close to the zone of transition from high to low fetch velocity. Also noted is that the slope of the fetch curves, V_F, in the transition zone is the same as the slope of the path of the peak energy waves, V_{pk}. In other words, V_F equals V_{pk} in this zone.

These observations might be viewed as swell forecast tools. If one wished, however, to forecast, through the use of weather maps, the arrival on the Pacific Coast of a swell train derived from a westward moving North Pacific storm using these observations, he could determine V_F directly from the weather maps but not V_{pk}. In this study V_{pk} was obtained from the swell data recorded at Monterey. In the following section a procedure is presented for estimating V_{pk} from the geostrophic wind speed in the fetch.

3. Velocity of Peak Energy Waves Determined from Surface Winds

a. Surface Wind Estimation

With the objective of using only data from weather maps, a method was devised for estimating the propagation velocity of the peak wave energy in the fetch from weather parameters for the purpose of comparing it with the fetch velocity. The propagation velocity was determined by first estimating a surface wind in the wind area. Assumptions involved in this somewhat complicated procedure were that the peak swell energy recorded at Monterey had in fact originated at the swell origin point determined from the f-t analysis of the five sets of swell data, and also that the seas at the swell origin point in each storm were fully arisen.

Considered together, these assumptions lead to the further assumption that the period of the energy peak in each swell set, T_{pk}, represents the period of the energy peak in the fully arisen sea. The surface wind speed, V_s, needed to produce a fully arisen sea having the value of T_{pk} recorded for each storm was then obtained directly from the Pierson-Neumann-James wave generation tables [1955]. The value of V_s so obtained, and V_g obtained from the fetch parameter graph (Figures 13 through 18), for the computed swell origin time, were then plotted for each storm. These data are shown in Figure 26.

The grouping of the points, as may be seen in the figure, was unexpectedly good. A linear fit to five of the points gave an average value for V_s of about 77% of V_g. The fact that this percentage falls within the range of values commonly used to reduce geostrophic winds to surface winds is considered to confirm the assumption that the seas were indeed fully arisen. It may also be noted that the point representing Storm 3B in Figure 26 is widely separated from the other plots, and that V_s is significantly larger than V_g. These irregularities provide further reason for dismissing this storm as the source of Swell Set 3, and this storm is not considered further in this study.

Having concluded that the sea was fully arisen at the swell origin point, it was then assumed that the seas approximated the fully arisen state throughout the storm history. This permitted computation of the group velocity of the peak-energy waves, V_T, as follows. The values of V_g for each six-hour interval in the storm history were reduced to values of V_s using the 77% factor found above. Then, using the PNJ energy data for fully arisen seas, the peak-energy periods were found for these surface winds, and the values of V_T for these periods were calculated. The reader is reminded that the values of V_T were computed

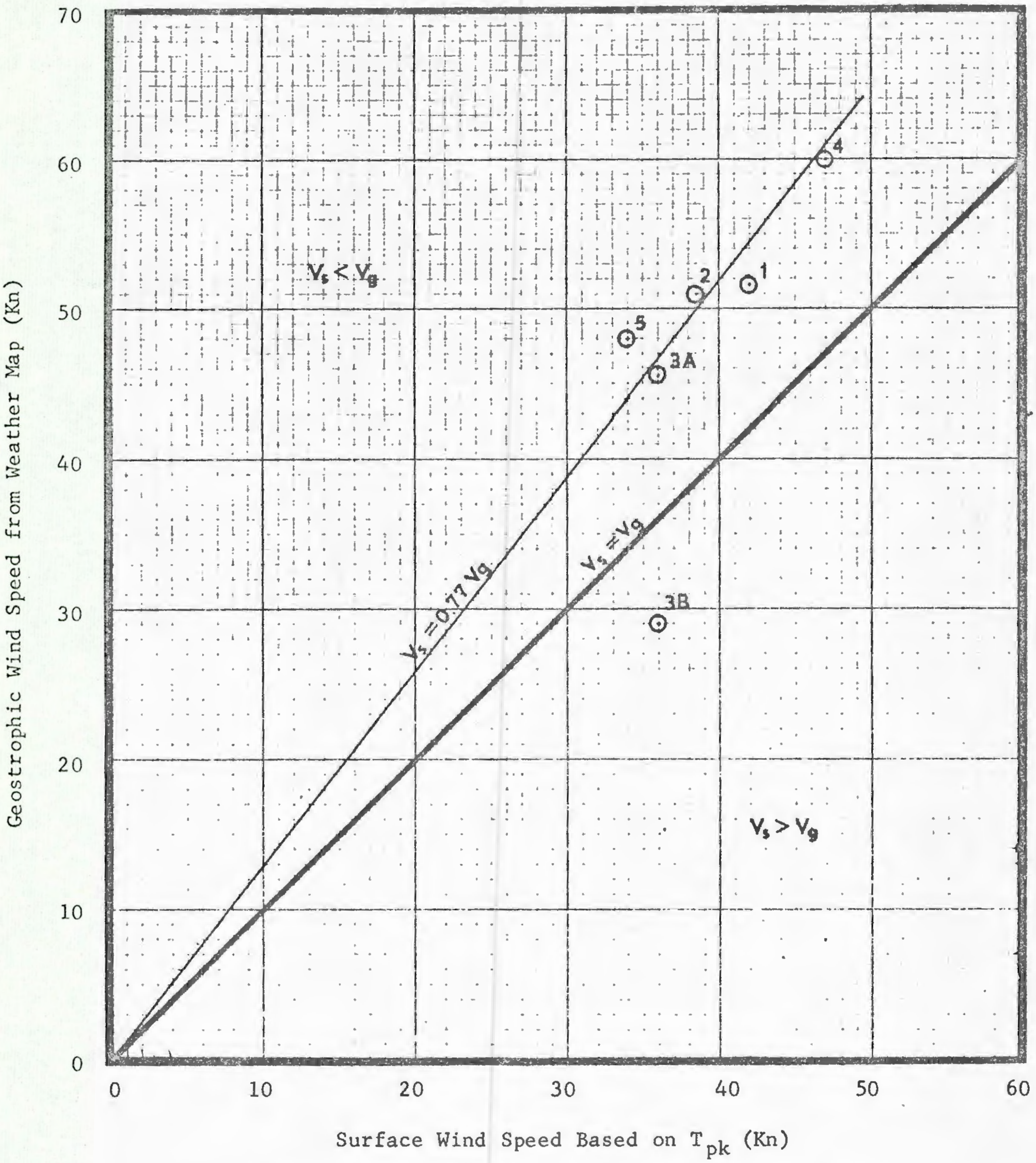


Figure 26: RELATIONSHIP BETWEEN GEOSTROPHIC AND SURFACE WINDS AT THE APPARENT SWELL SOURCE

entirely from weather map data. Figures 27 through 31 show a comparison of these velocities with the fetch velocities for each storm analyzed. In each figure the apparent origin time of the observed swell train is indicated by a small arrow on the time axis.

b. Comparison of V_F and V_T

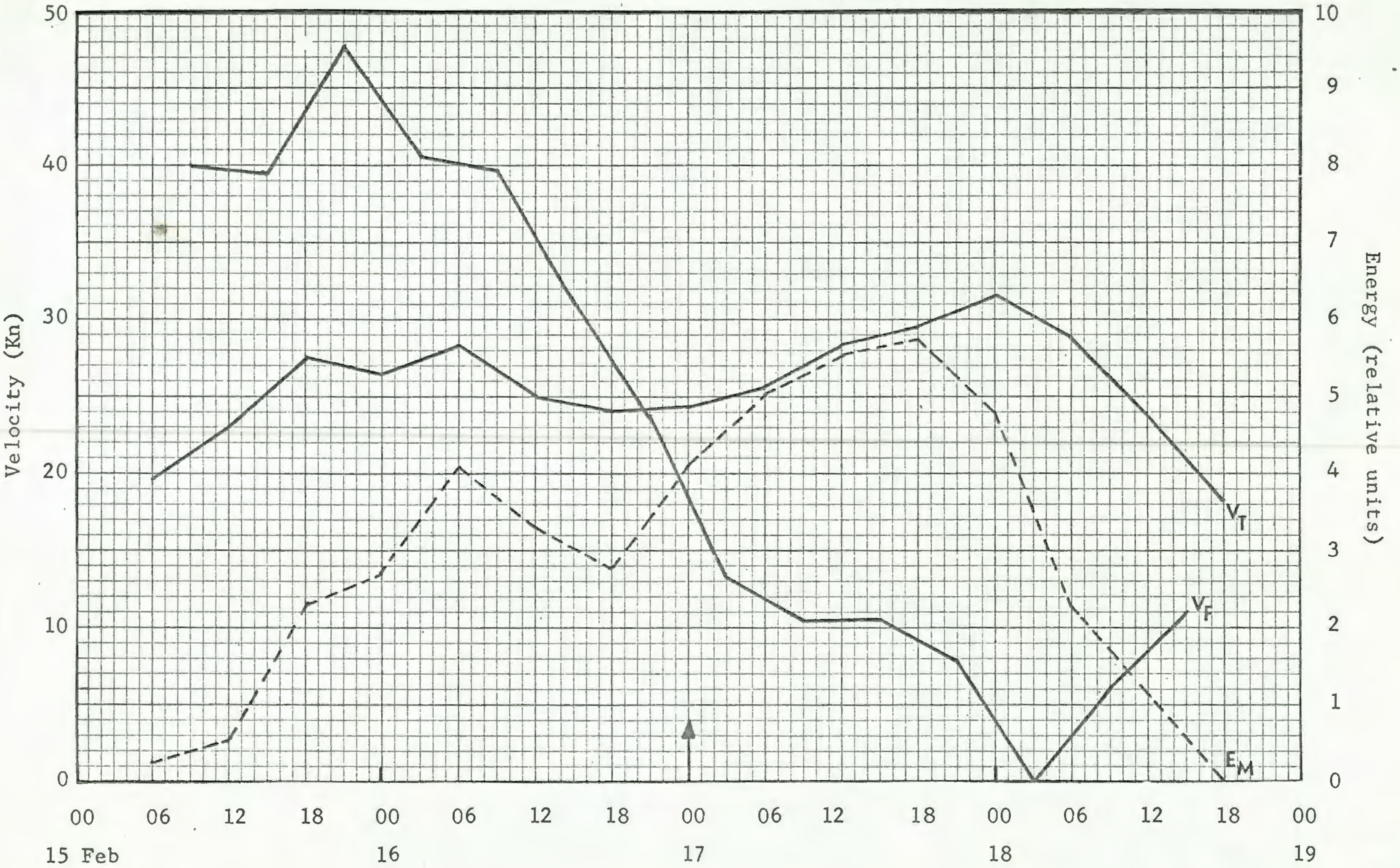
The curves of V_F and V_T follow a similar trend in four of the five storms considered. In the early stages of these storms $V_F > V_T$ and in the later stages $V_F < V_T$. Between these stages, the graphs show one or more crossing points where $V_F = V_T$ and conditions are presumably most suitable for a maximum buildup of energy in the fetch. In the case of Storm 3A, however, the wind field was a fast-moving one with relatively low wind speeds, and V_F was therefore always greater than V_T.

It was expected that the apparent swell origin times derived from the f-t analyses of the wave records might coincide closely with the times at which $V_F \doteq V_T$. This correlation existed for Storm 1 only. In all of the other storms, the values of V_F and V_T differed by 12 knots or less at the origin times; however, the origin times followed by many hours the times at which the curves of V_F and V_T crossed.

Although the results of this experiment were inconclusive, an approach based on relative velocities of the fetch and the peak-energy waves seems to hold promise for producing a simple method of estimating the arrival time and period of the peak swell at a distant station from examination of the storm history alone.

D. ENERGY PROPAGATED TO MONTEREY

The previous analysis considered, in effect, the energy level in the wind area without regard to the propagation of this energy as swell. After leaving the fetch, the swell energy is affected by two processes:



February 1967 (GMT)

Figure 27: GROUP VELOCITY OF PEAK ENERGY WAVES, FETCH VELOCITY, AND ENERGY ARRIVING AT MONTEREY; STORM 1

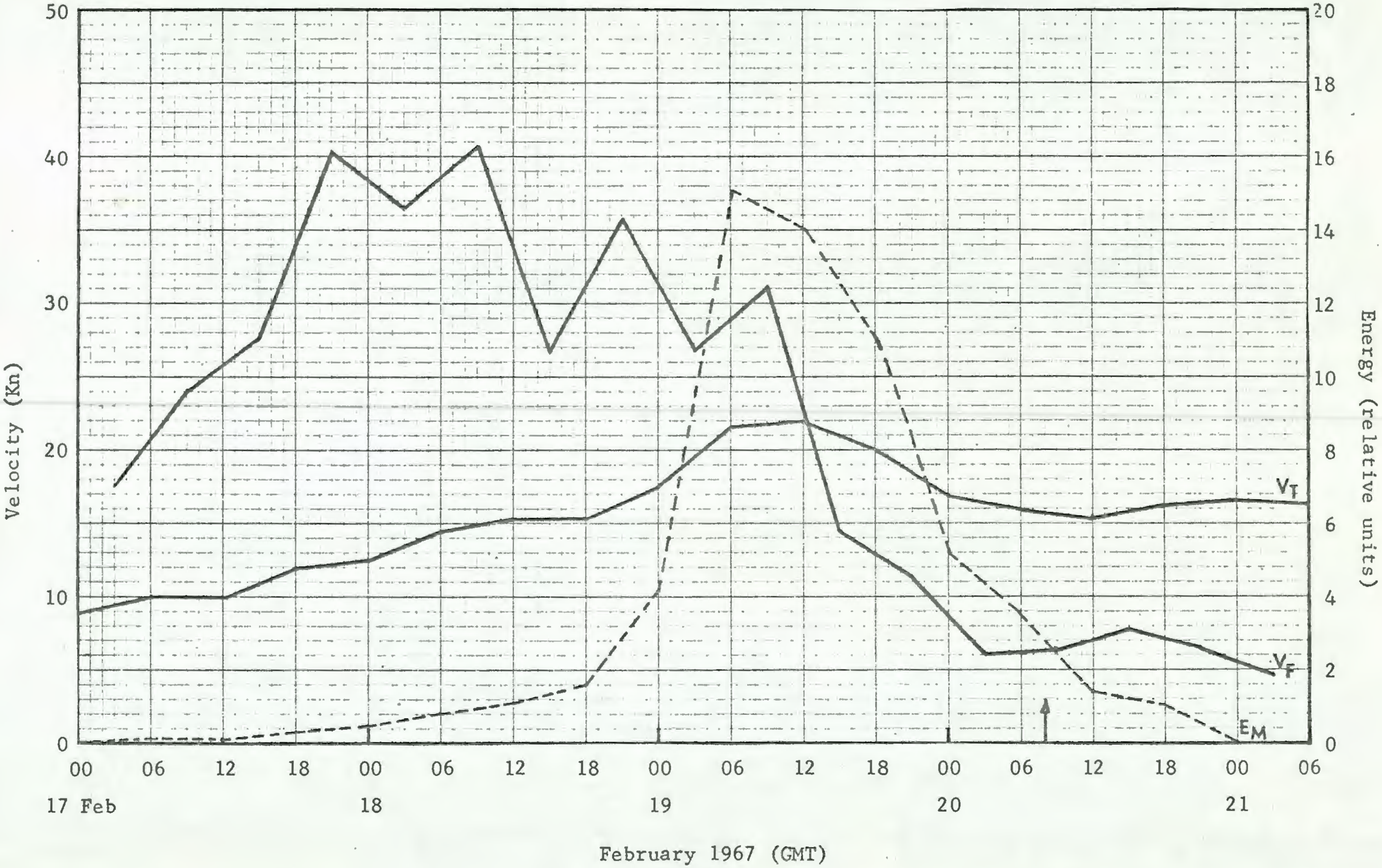


Figure 28: GROUP VELOCITY OF PEAK ENERGY WAVES, FETCH VELOCITY, AND ENERGY ARRIVING AT MONTEREY; STORM 2

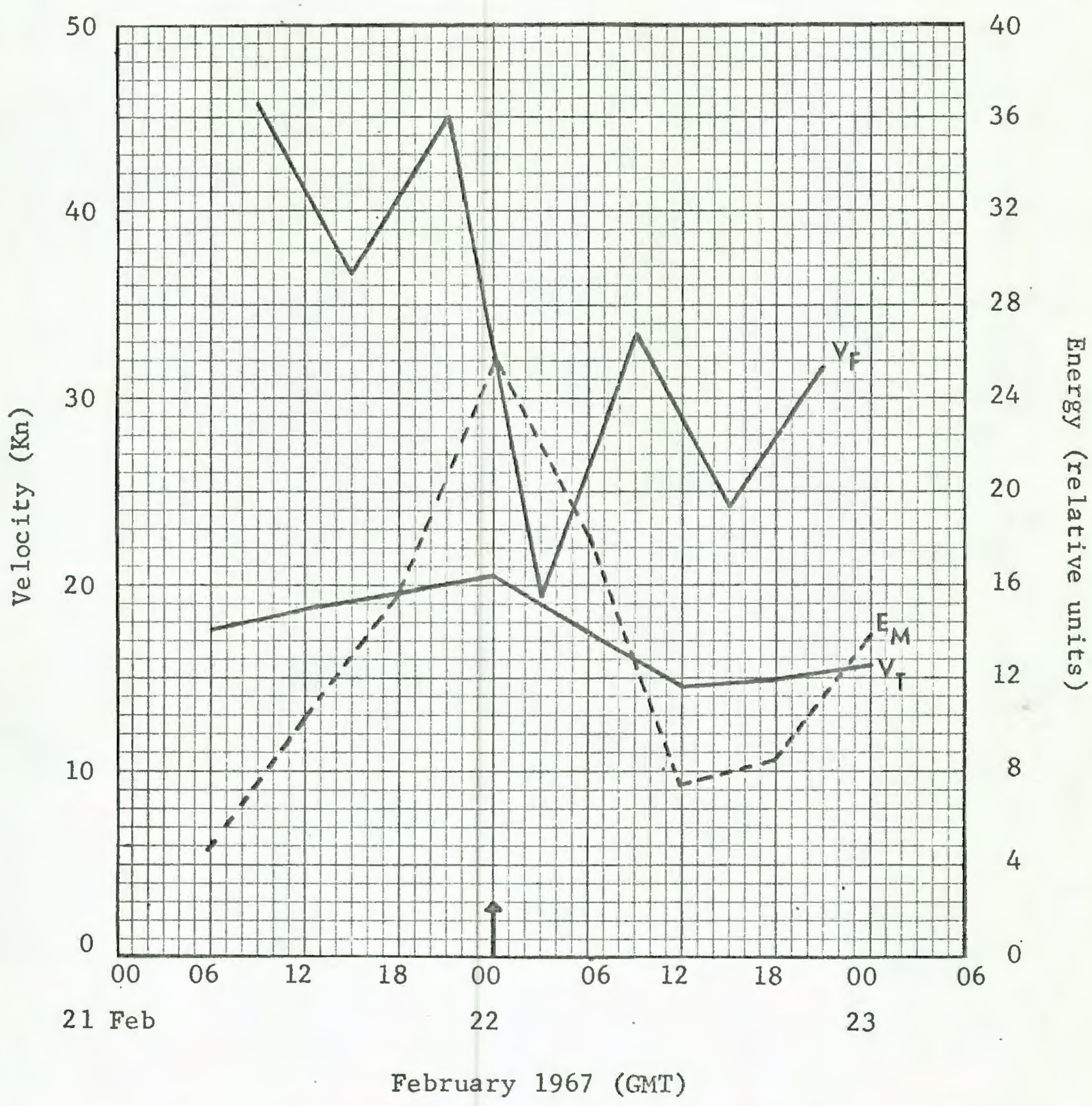


Figure 29: GROUP VELOCITY OF PEAK ENERGY WAVES, FETCH VELOCITY, AND ENERGY ARRIVING AT MONTEREY; STORM 3A

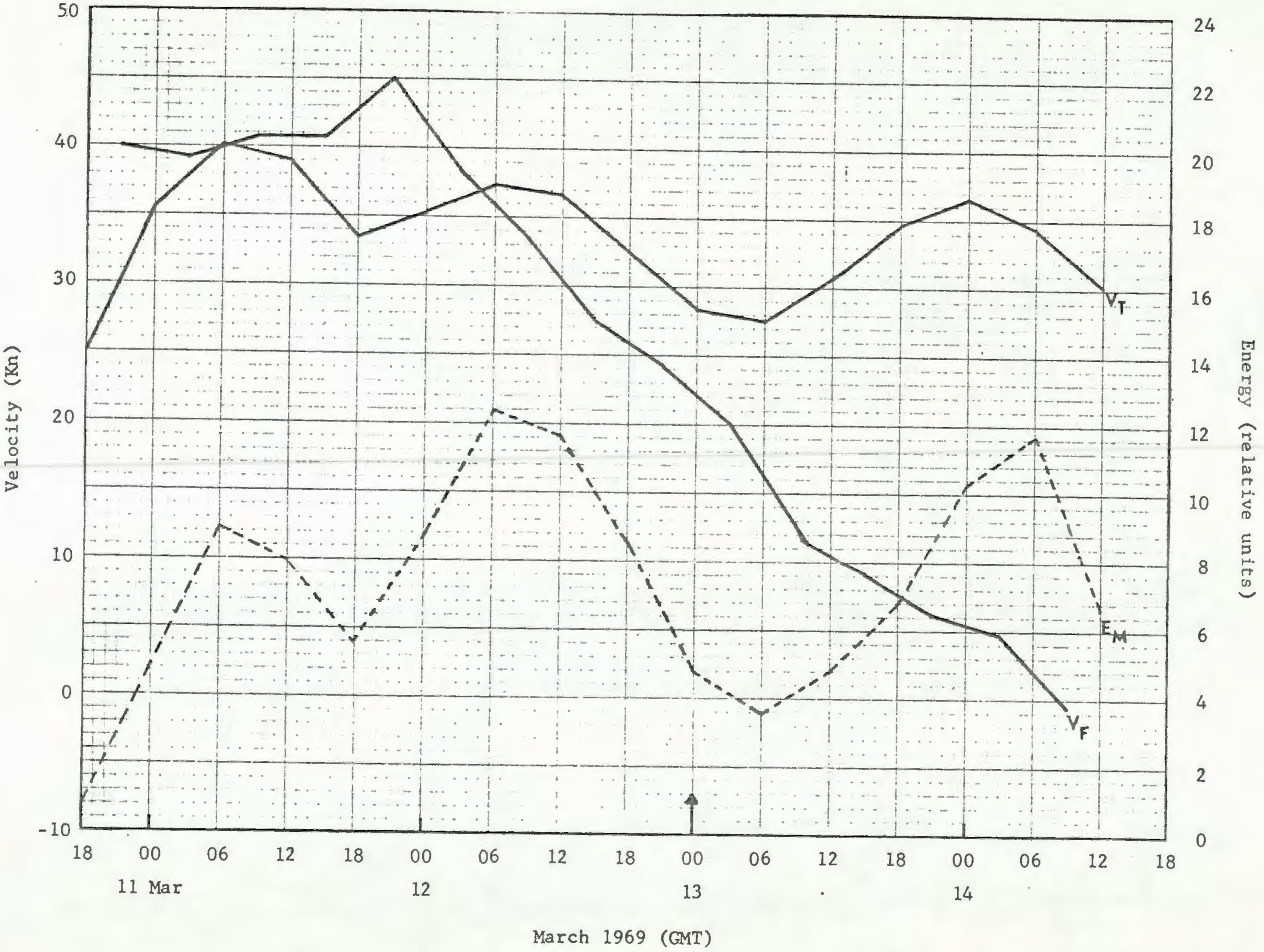


Figure 30: GROUP VELOCITY OF PEAK ENERGY WAVES, FETCH VELOCITY, AND ENERGY ARRIVING AT MONTEREY; STORM 4

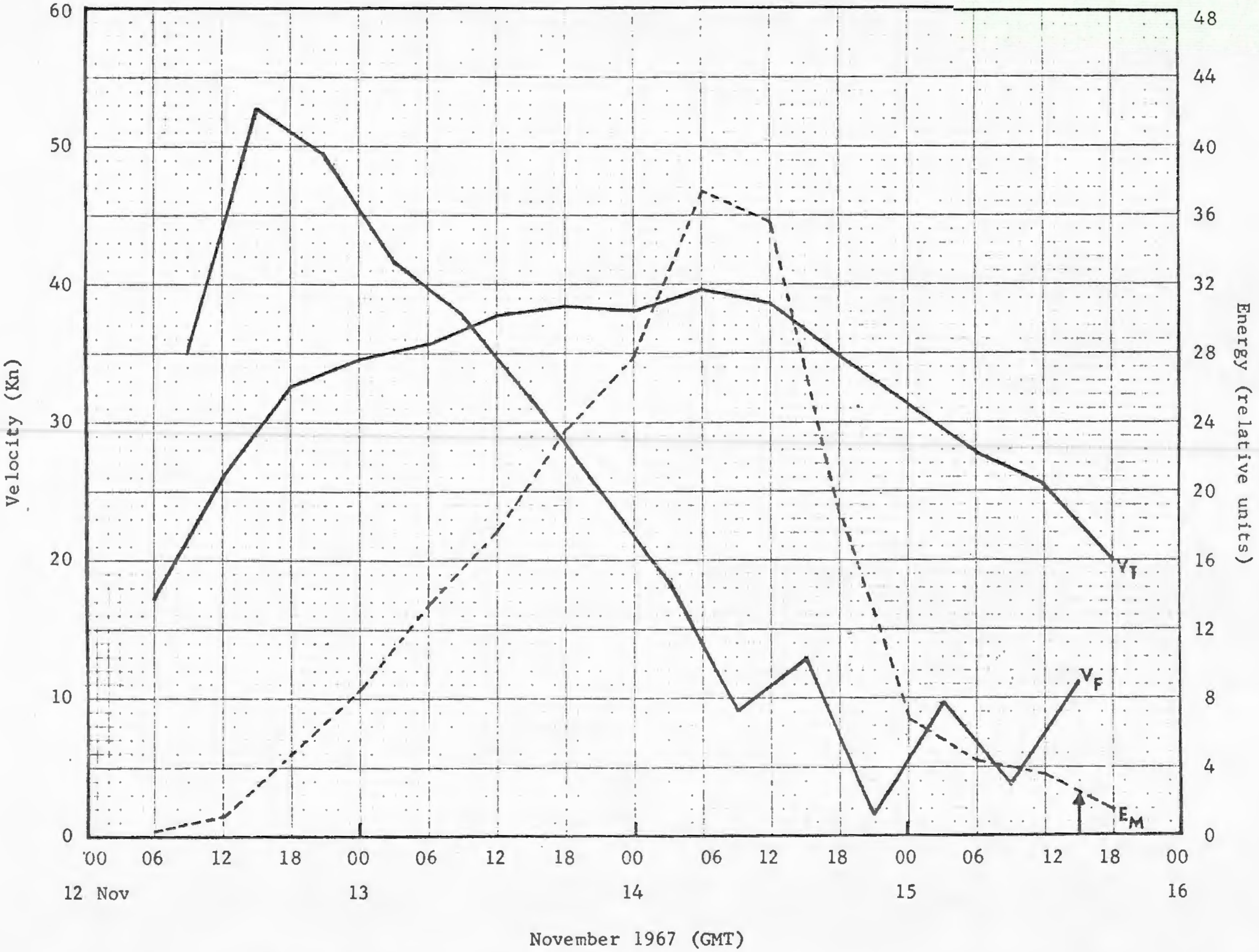


Figure 31: GROUP VELOCITY OF PEAK ENERGY WAVES, FETCH VELOCITY, AND ENERGY ARRIVING AT MONTEREY; STORM 5

frequency dispersion and angular spreading. The effect of these processes was taken into account by combining them to form a swell energy factor, E_M, defined as the product of the energy in the fetch, E, a dispersion factor, δ, and the angular spreading factor S. E_M is a relative measure of the swell energy arriving at Monterey.

The value of E_M was computed for every six-hour interval during the history of each storm. The fetch energy was obtained from the PNJ manual using the values of V_s computed in Section C above and assuming fully arisen seas. Dispersion, as measured by the bandwidth of frequencies arriving at Monterey, is a function of the distance from Monterey to the fetch. Accordingly, a dispersion factor, 1/D, was used to give a crude approximation of the energy reduction due to this process. Values of the angular spreading factor were obtained from the PNJ manual using the values of angular fetch width given in Figures 13 through 18. The resulting values of E_M are shown in Figures 27 through 31.

It was anticipated that the apparent source time of each swell train, shown by the arrow in each figure, might be found to occur at or near the time of peak values of E_M, however the results proved inconclusive. A probable reason for lack of success is that the assumption of a fully arisen sea throughout the history of each storm is gross approximation, except apparently near the time of swell origin.

V. CONCLUSIONS

Five selected swell trains recorded at Monterey and the storms that produced them were analyzed with the purpose of determining the conditions prevailing in the wind field at the time of origin of the peak swell energy recorded. The distance and time of origin of each swell train was determined from frequency-time analysis of the wave records, and this information was used to identify, on the weather maps, the storm in which the waves were generated. An objective procedure was developed for delineating, on the weather maps, the fetch that produced the swell, and for obtaining the geostrophic wind speed and other pertinent parameters.

Distance-time graphs were prepared for each storm showing the development of the fetch in terms of its size and speed. Each graph revealed a distinct zone of transition from high fetch velocity in the early stages of the storm to low velocity in the later stages as the fetch moved toward Monterey. The point of origin of each swell train was found to lie within the delineated fetch in the case of four of the storms, and within 50 nm of the fetch in the remaining case. In addition, the origin point was found to be located within the velocity transition zone. The apparent origin points were found to lie near the rear of the fetch during the high velocity stage of the transition zone (Storms 1 and 4), near the center of the fetch during the middle of the transition zone (Storm 3A), and near the front of the fetch during the low velocity stage of the transition (Storms 2 and 5). These locations agree with the expected origin areas of the largest waves produced in a fast moving fetch that decelerates suddenly. Another important observation from the distance-time analysis is that the peak energy swell were produced when their group velocity was equal to the velocity of the fetch, a condition in which large wave energy can be generated because of a long effective wind duration.

Assuming that the peak swell period recorded at Monterey was the same as the peak energy period of the sea in the fetch at the computed swell source, and that the sea was fully arisen, the surface wind speed considered to have produced the sea was then determined from the PNJ energy relations. The surface wind so obtained, and the geostrophic wind derived independently from the weather maps at the swell origin point, were then compared. For the great cyclonic storms studied, the ratio of the surface wind to the geostrophic wind was found to average 0.77 and to range between 0.70 and 0.80. This ratio agrees well with published values obtained by the usual method of direct comparison. The approach used here offers considerable potential for exploring the value of this ratio further.

The surface to geostrophic wind ratios obtained are considered to confirm the assumption that the swell recorded at Monterey were generated when the seas were indeed fully arisen. Further, the consistency of these results, mainly the coincidence of the computed swell source with the wind area and the reasonable values found for the surface to geostrophic wind ratio, support the initial determination that no shift in the period of the peak swell energy occurred due to shoaling or refraction processes off Monterey.

Two attempts were made to find a means of using weather maps alone to determine the time when the peak swell eventually arriving at Monterey emerges from the storm. In the first attempt, by assuming fully arisen conditions throughout the fetch history, the group velocity of the peak energy waves that would be generated under these conditions was calculated for each six-hour interval of the history. This velocity was then compared with the fetch velocity with the expectation that the swell peak would emerge about the time when the two velocities were equal or nearly so. The second attempt consisted of devising an empirical swell-energy factor that would indicate when the peak energy should arrive at Monterey. This factor incorporated the energy produced in the sea and the swell decay processes of frequency dispersion and angular spreading. The results of these experiments were inconclusive. They appear to indicate that the assumption of fully arisen sea conditions throughout the fetch history, upon which both attempts were based, is inaccurate except near the time of swell origin.

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13. ABSTRACT

Selected swell wave records from Monterey, California and the associated weather maps were analyzed to determine at what stage in the storm history the peak energy in the swell trains was produced. The apparent origin of the swell, derived by frequency-time analysis of the wave records, was found to lie within the fetch determined from the weather maps, and to occur during the stage in the storm history when the fetch velocity was rapidly decreasing. The group velocity of the peak energy swell was found to equal the fetch velocity at the time of swell origin, a condition suitable for the generation of large wave energy because of a long effective wind duration. By assuming fully arisen seas at the apparent swell source, an average value of the ratio of surface to geostrophic wind speed of 0.77 was obtained. This value was derived from surface winds obtained from the wave data and geostrophic winds obtained from the weather maps. These results confirm the assumption that the peak energy swell was generated in fully arisen seas, and that no shift occurred in the peak swell period in shallow water off Monterey.

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